Recent and Emerging Science and Applications Relating to Precipitation and Atmospheric Rivers in the Western U.S.

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16 February 2012

Water Cycle Colloquium
NASA/Jet Propulsion Laboratory
Pasadena, California

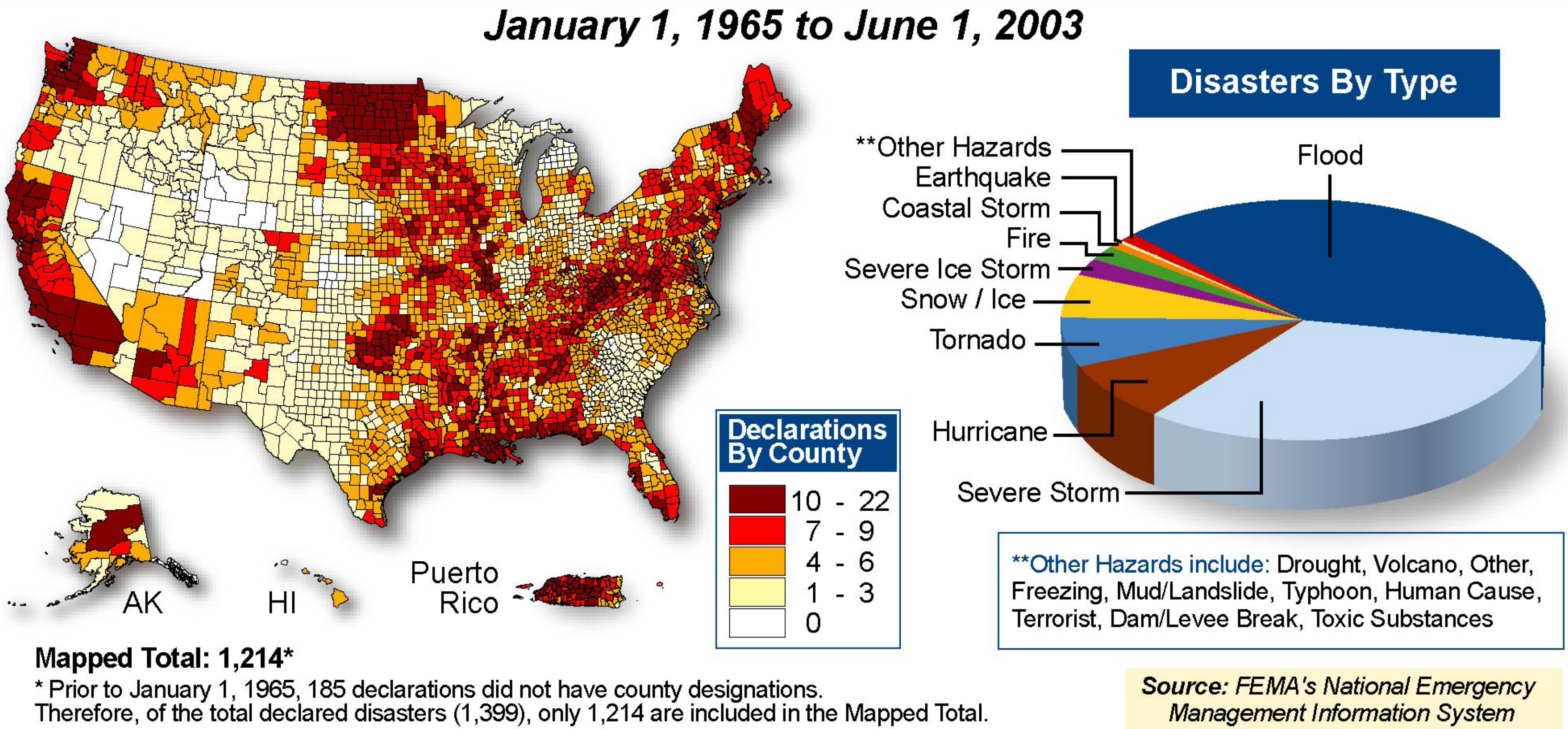
Outline

- Motivation
- Characteristics of extreme precipitation in the Western U.S
- Atmospheric rivers – a key player in the Western U.S.
- “CalWater” experiment (2009-2012)
- “WISPAR” experiment (2011)
- “CalWater 2” (under development)
- Summary

Motivation

- Flooding is the most common natural hazard and has major socio-economic impacts
- Water supply is limited (especially in the West)
- Precipitation and runoff are some of the most challenging parameters to forecast on short times scales or to project in a changing climate

Presidential Disaster Declarations



- Floods annually cause 80 fatalities + $5.2 B damage on average (~50% of the annual average U.S. natural disaster losses)
- Note that losses from drought are not typically tracked this way

Source: NOAA Economic Statistics, 2006

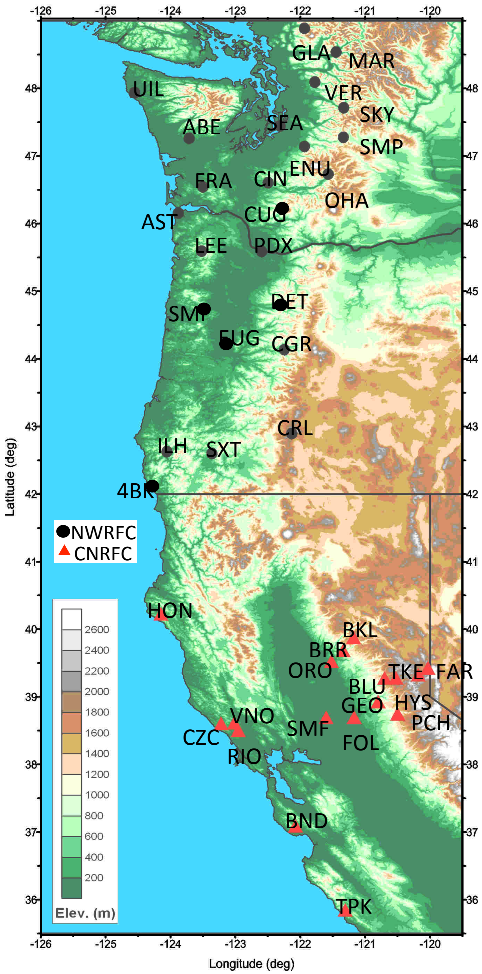
Assessment of Extreme Quantitative Precipitation Forecasts (QPFs) and Development of Regional Extreme Event Thresholds Using Data from HMT-2006 and COOP Observers

F. M. Ralph, E. Sukovich, D. Reynolds, M. Dettinger, S. Weagle, W. Clark, and P. J. Neiman

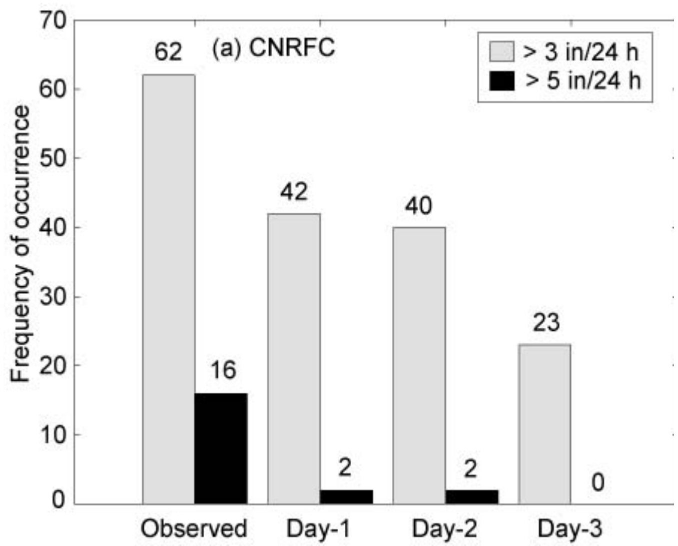
Journal of Hydrometeorology (December 2010)

Of the 20 dates with >3 inches of precipitation in 1 day, 18 were associated with ARs.

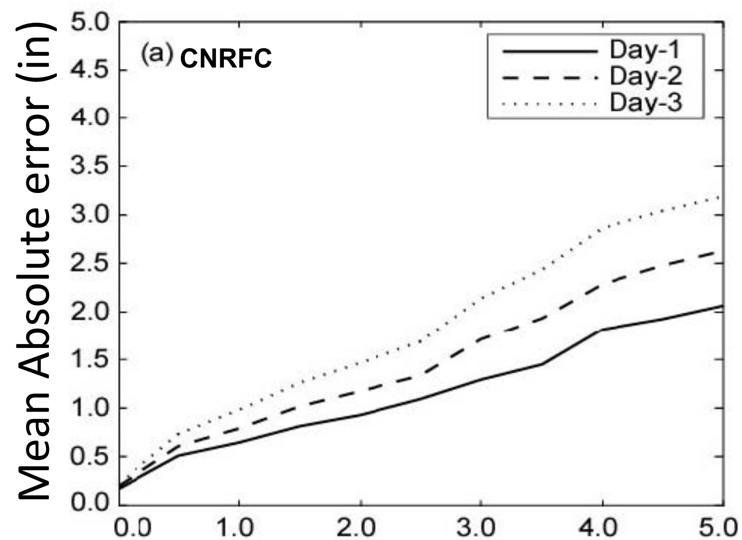
The Forecasting Challenge



41 West Coast sites were used



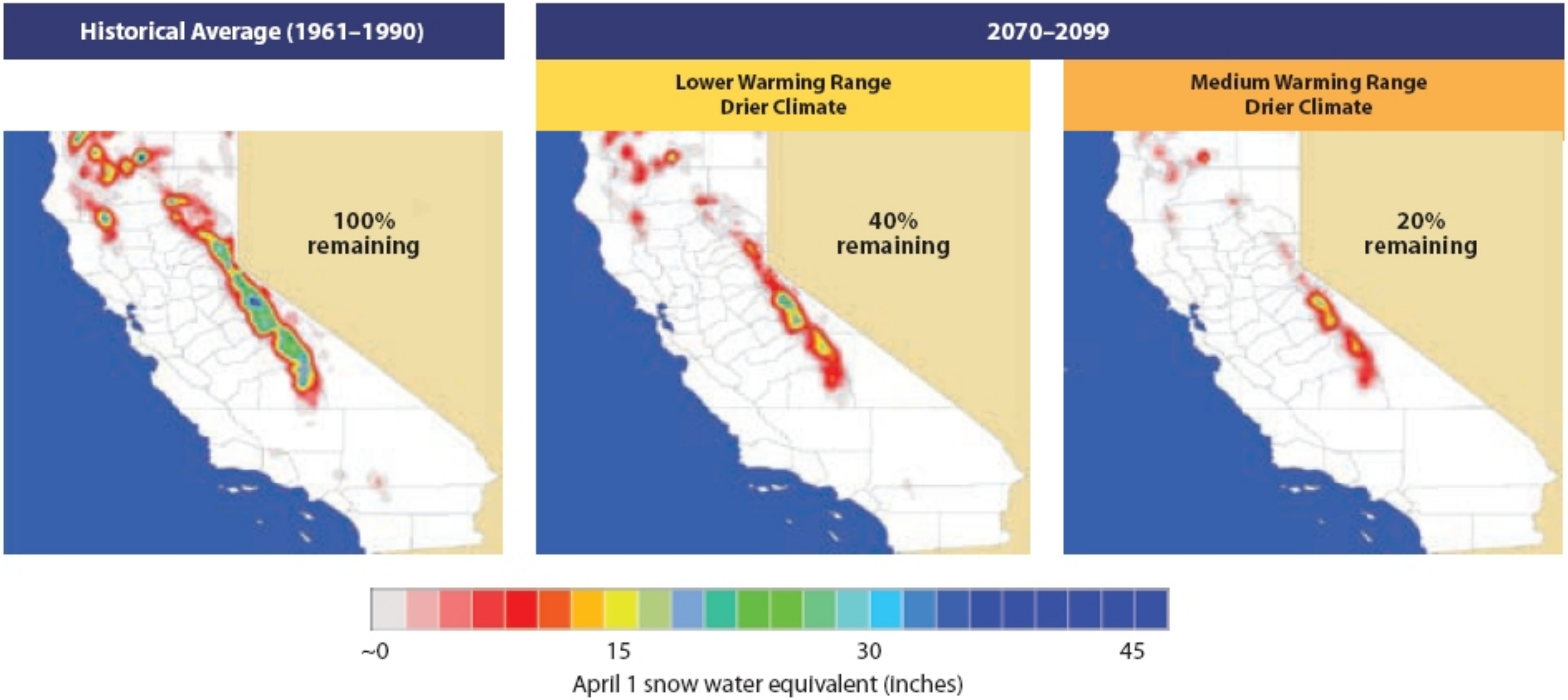
Forecasting large precipitation amounts is difficult



On average forecasts are 50% less than observations

Decreasing California Snowpack

Snow pack acts as a natural reservoir for summer and fall water supply.
Its capacity is projected to decrease significantly in a warmer climate.



Under an ensemble of climate scenarios, there is marked reduction in spring snow pack:

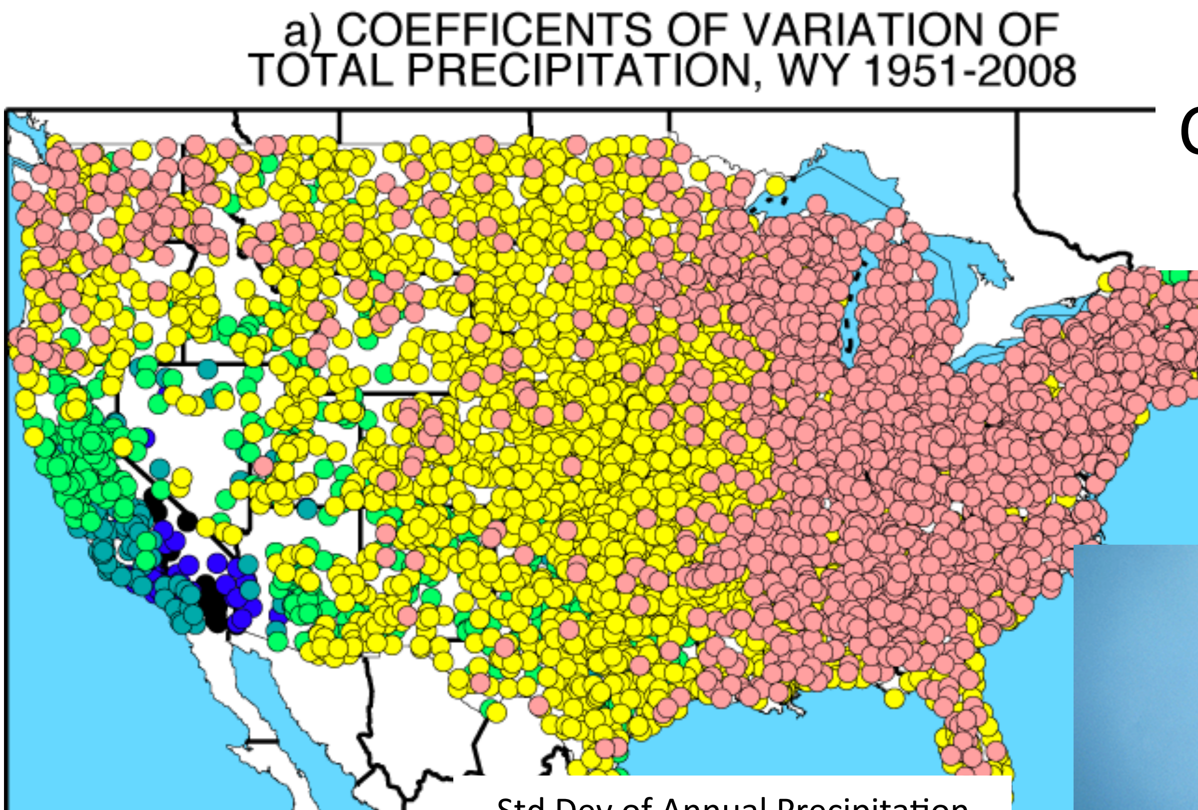
- by 2100 the chance of achieving historical median SWE falls to about 10%.
- by 2100 the chance of SWE at or below 10 percentile historical rises to about 40%.

“Water is the next oil.”

- **Conclusion of a National Security report on risks associated with changing climate.**


Precipitation extremes in the West

Interannual variability is high in the West

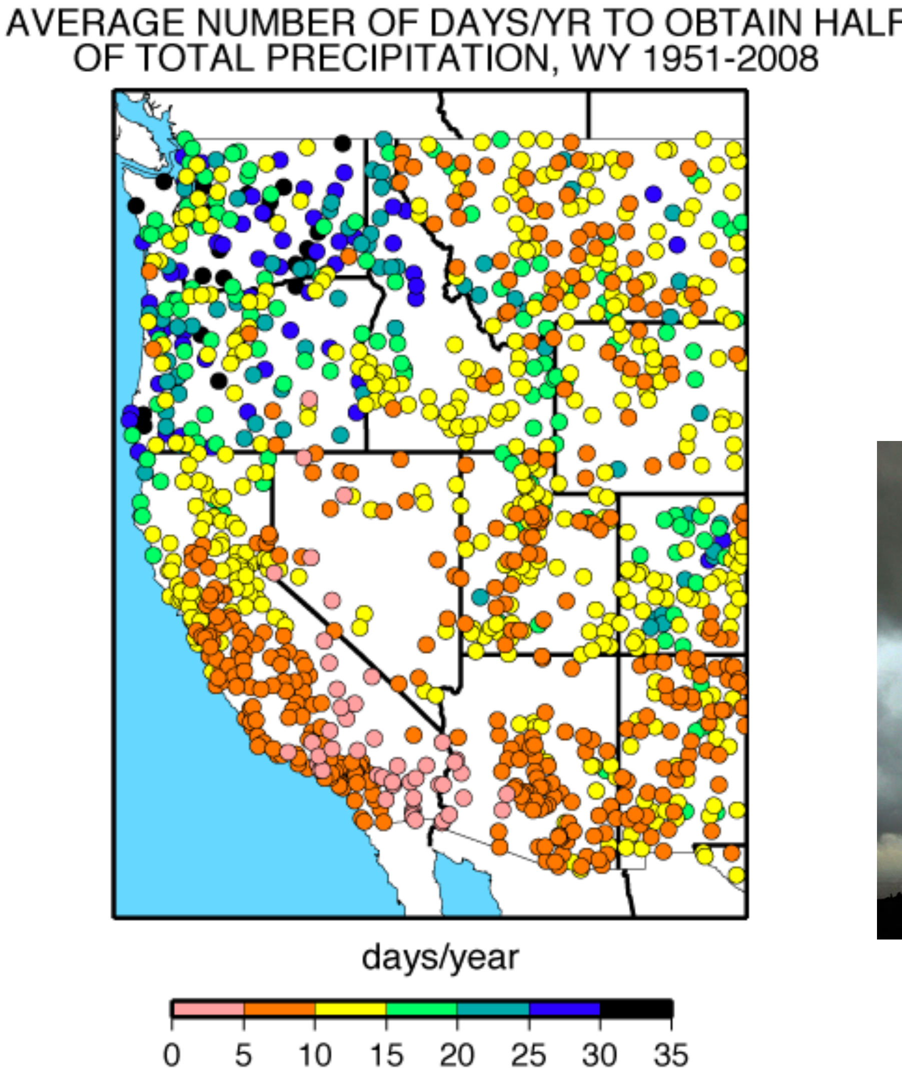


California precipitation
is uniquely variable

$$\frac{\text{Std Dev of Annual Precipitation}}{\text{Mean Annual Precipitation}}$$

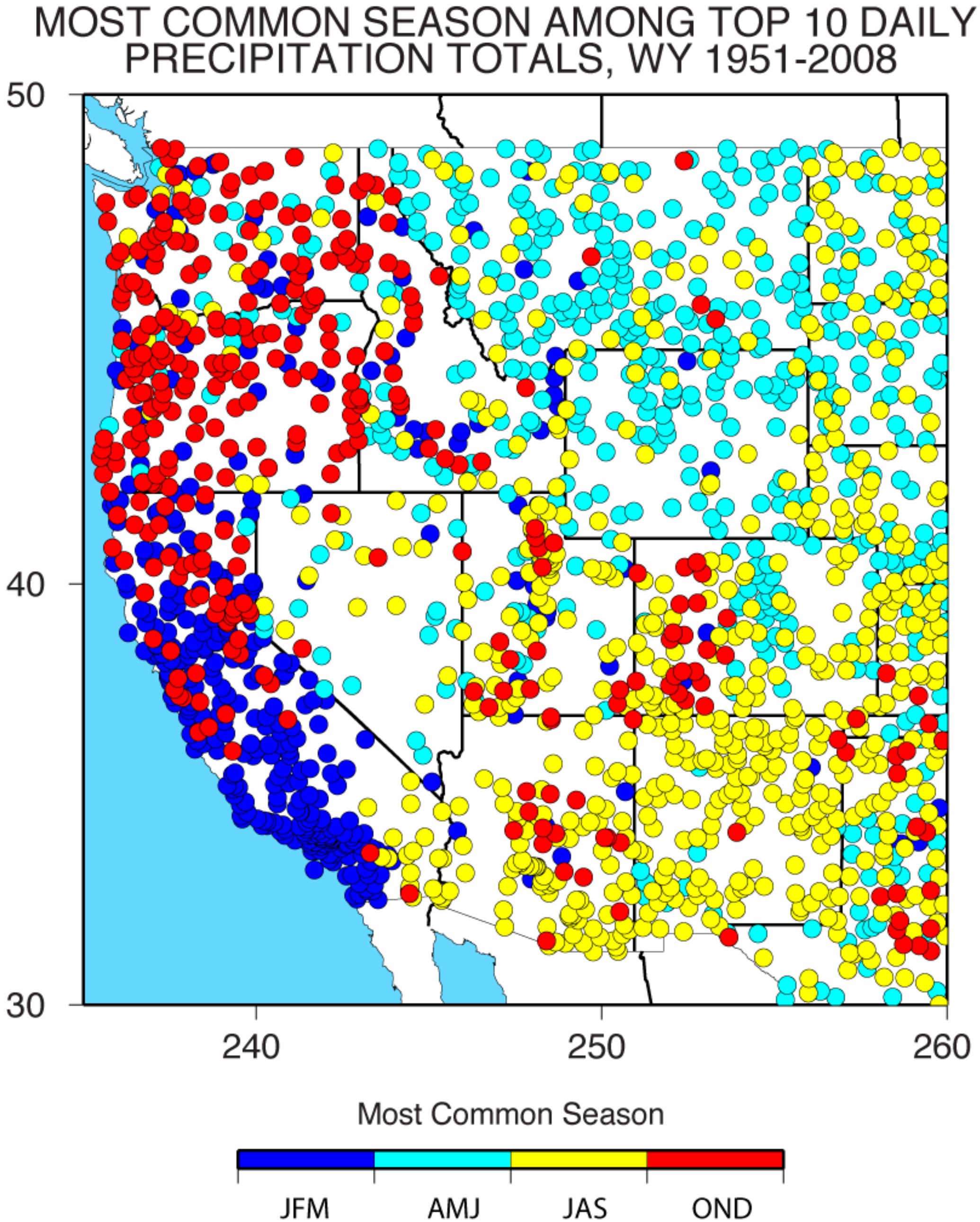
Dettinger et al, Water, 2011

Extreme precipitation is key to water supply



Just a few storms each year form the core of our water supplies

Dettinger et al, Water, 2011



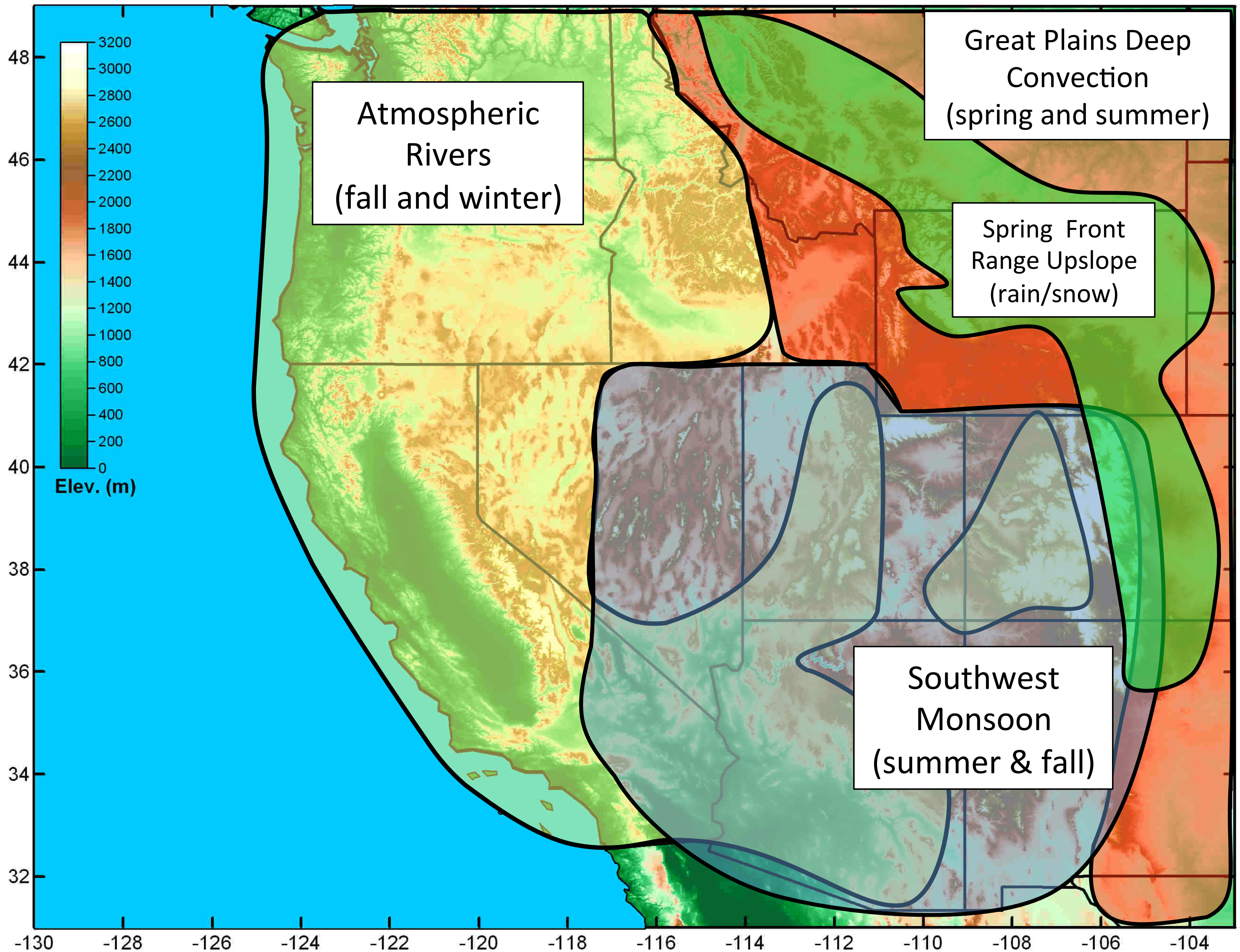
From a white paper by Ralph et al, 2011

Analysis from COOP daily precipitation observations.

-Each site uses at least 30 years of data
-The top 10 daily precip dates are found
-The season for which most of these top-10 dates occurred at that site is color coded.

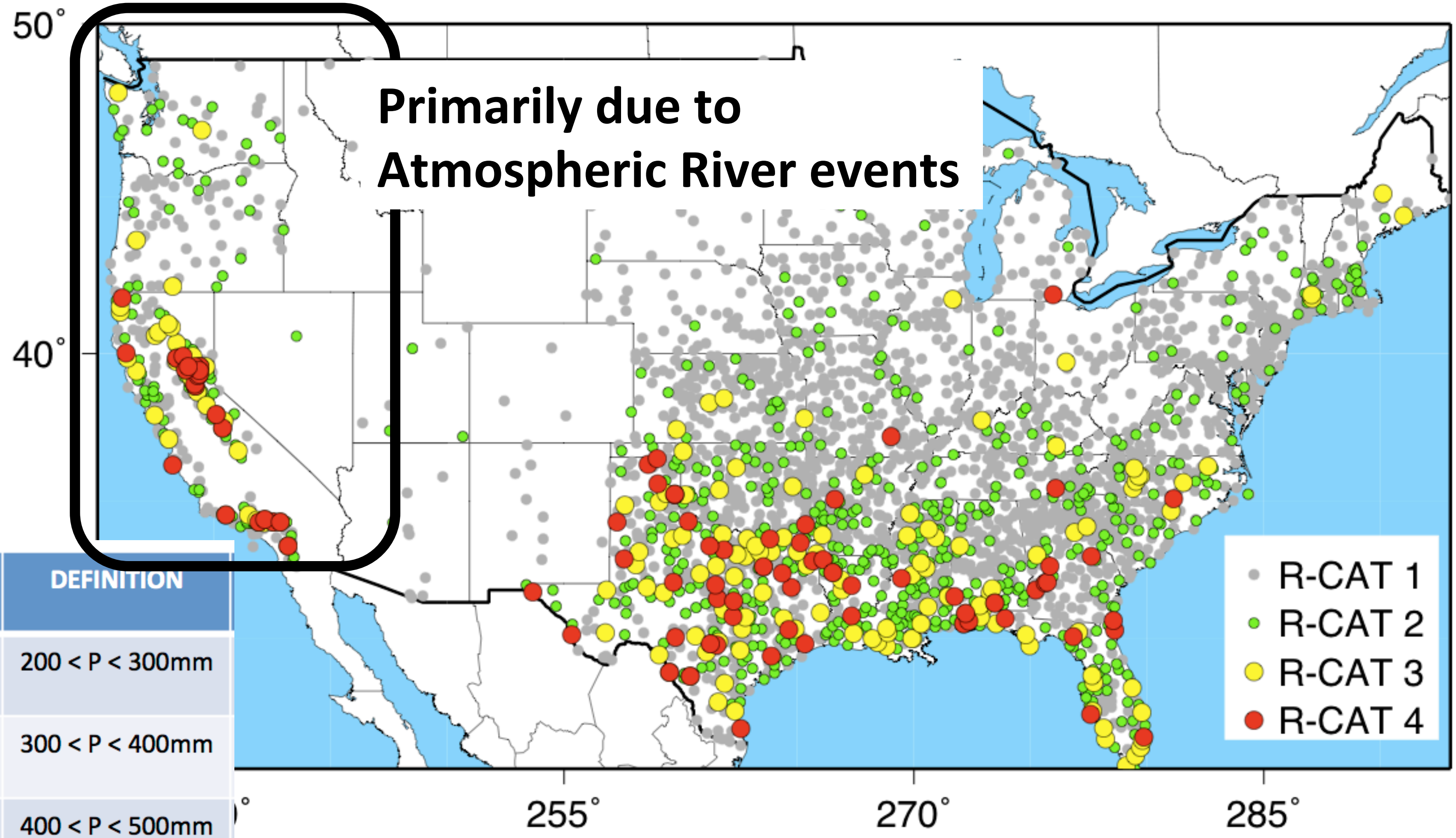
-The affect of the southwest Monsoon is seen in yellow dots in AZ, CA, UT, NM, and CO (yellow sites in the Great Plains are not monsoon dominated)
-The affect of atmospheric rivers is highlighted by blue and red dots, including almost all of each coastal state, plus inland penetration of AR impacts into AZ, Western CO, SW and Central UT, and ID.
-Great Plains convective events focus in spring (light blue dots) and summer (yellow).
-Colorado front range is mostly spring.
-Nevada is a mixture.

Schematic illustration of regional variations in the primary weather phenomena that lead to extreme precipitation, flooding and contribute to water supply in the Western U.S.



CALIFORNIA'S STORMS ARE AS BIG AS ANY IN THE COUNTRY

LARGEST 3-DAY PRECIPITATION TOTALS, 1950-2008

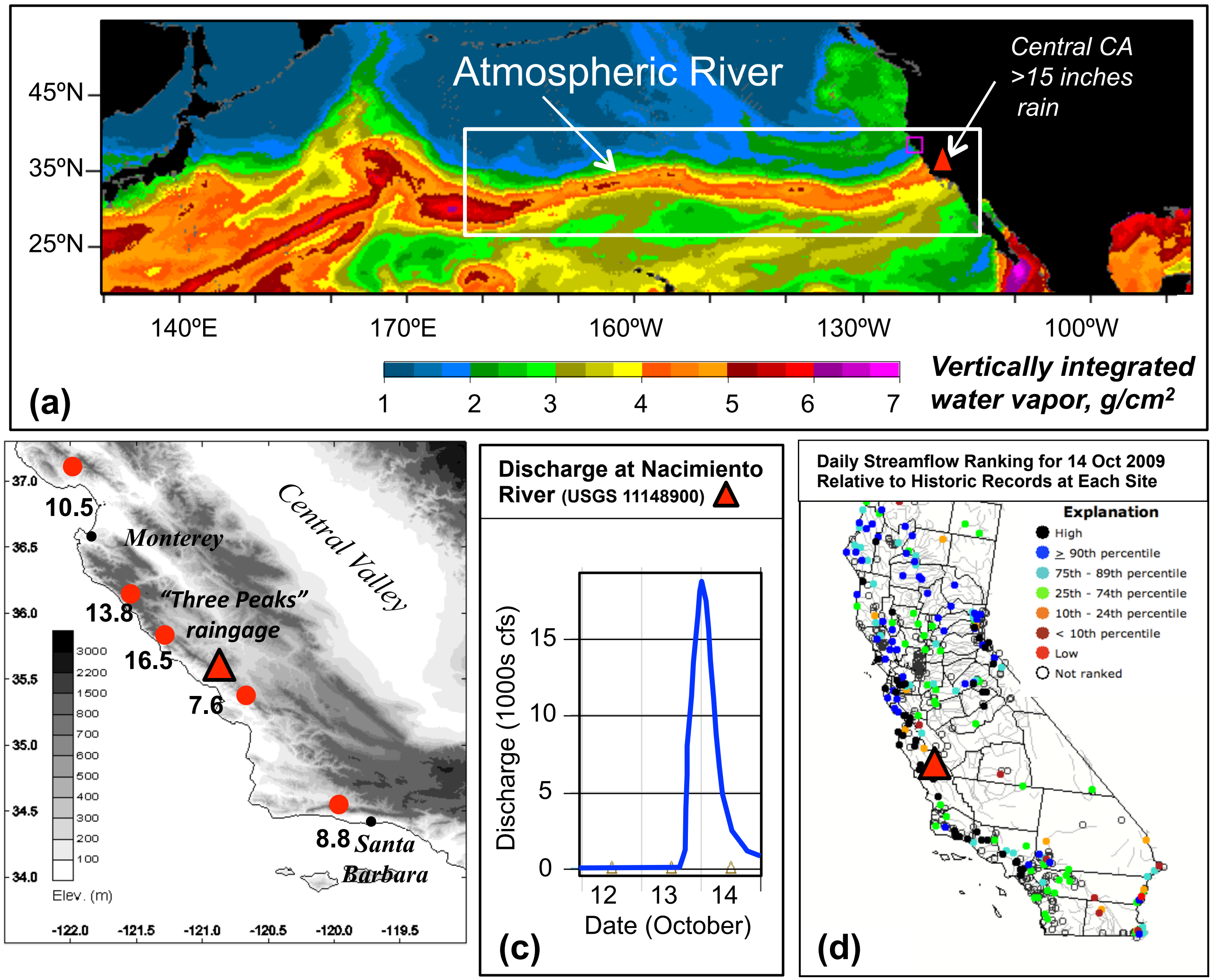


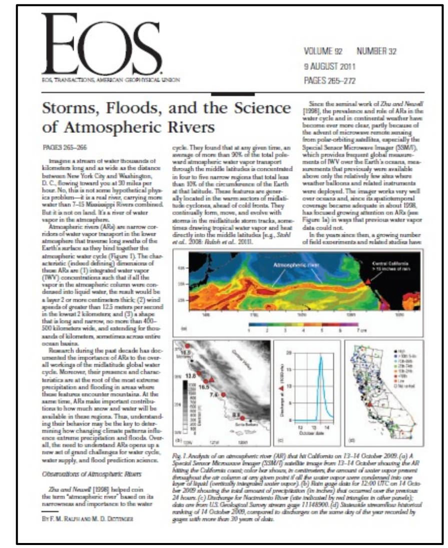
R-CAT	DEFINITION
1	200 < P < 300mm
2	300 < P < 400mm
3	400 < P < 500mm
4	P > 500mm

Ralph, F.M., and Dettinger, M.D., Historical and national perspectives on extreme west-coast precipitation associated with atmospheric rivers during December 2010: Bulletin of the American Meteorological Society, (in press, Nov 2011)

Atmospheric Rivers

Research has Identified Atmospheric Rivers as the Primary Meteorological Cause of Extreme Precipitation & Flooding on U.S. West Coast




EOS

VOLUME 92 NUMBER 32
9 AUGUST 2011
PAGES 265–272

Storms, Floods, and the Science of Atmospheric Rivers

Ralph, F.M., and M.D. Dettinger, 2011: Storms, Floods and the Science of Atmospheric Rivers. *EOS, Transactions, Amer. Geophys. Union.*, **92**, 265-266.

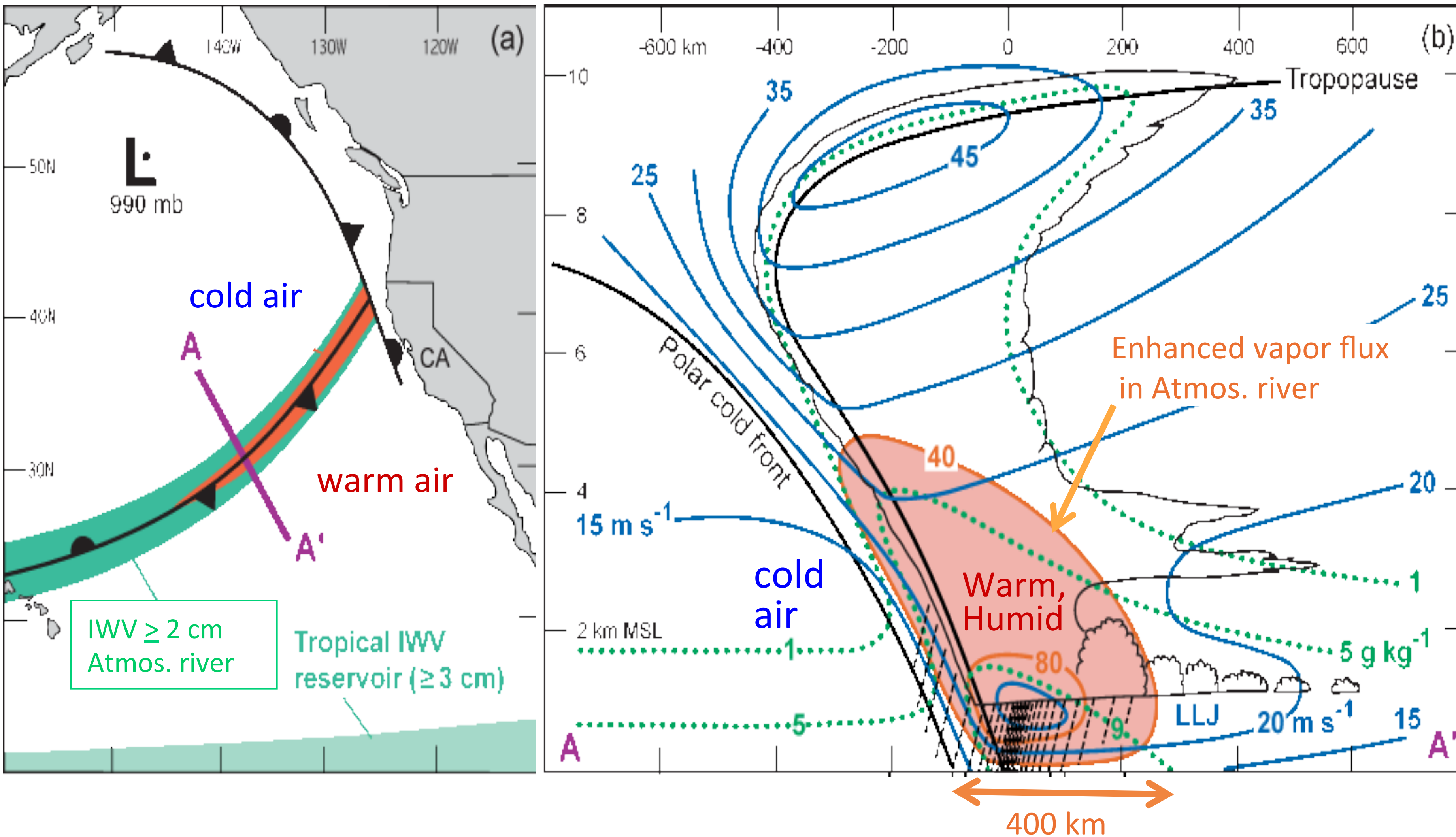
http://hmt.noaa.gov

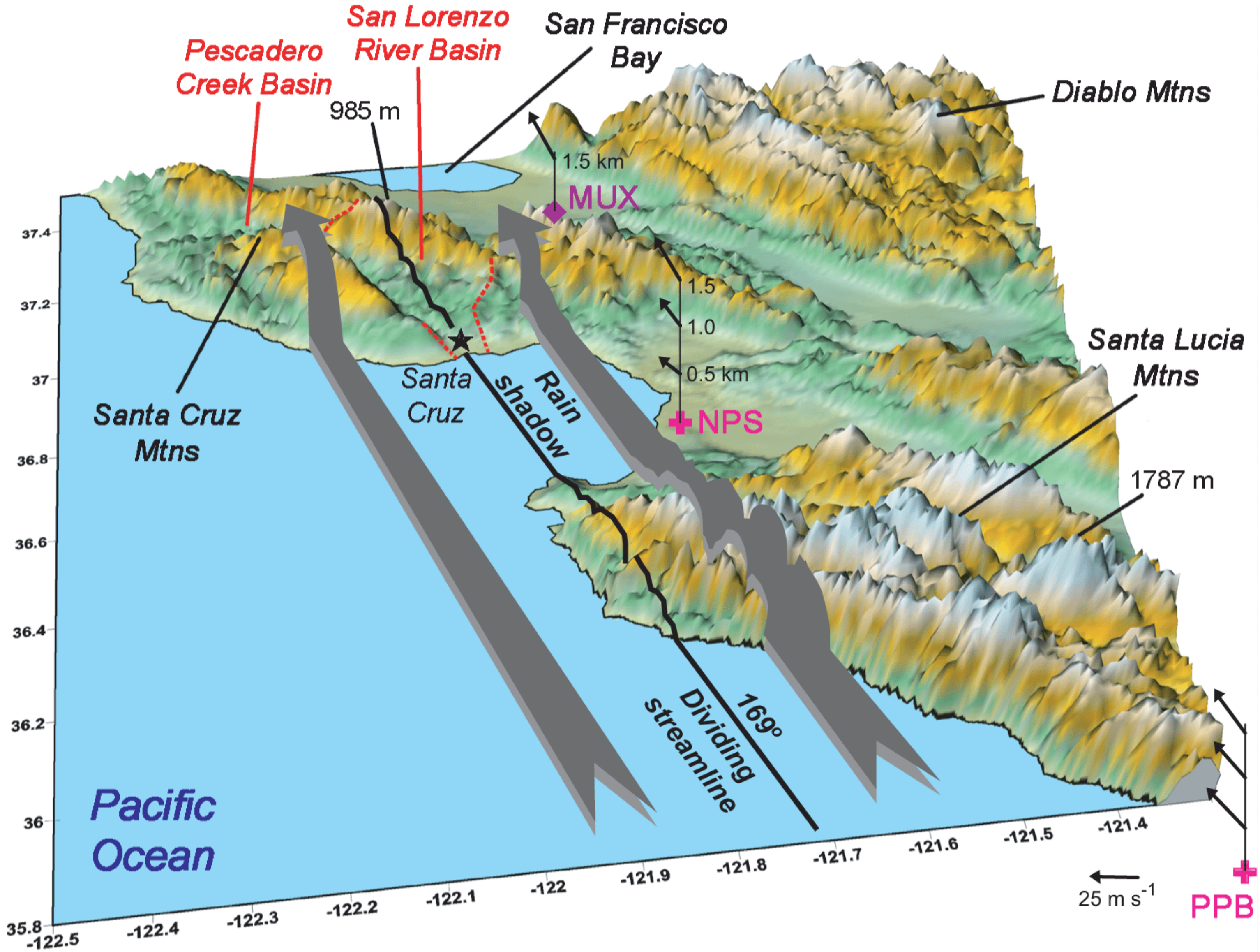
NOAA's HMT Fostered AR Research and Links to Forecasting

- NOAA's Hydrometeorology Testbed (HMT)
  - Connects researchers, forecasters and forecast users
  - Has been researching and developing prototypes on extreme precipitation in California since 2003
  - Testing and applying results to the Pacific Northwest
  - Builds on earlier experiments from 1997-2002
- Lessons learned from HMT have been documented in over 50 formal peer-reviewed technical publications
  - http://hmt.noaa.gov/pubs/

Observational studies by Ralph et al. (2004, 2005, 2006) extend model results:

1) Long, narrow plumes of IWV >2 cm measured by SSM/I satellites considered proxies for ARs.
2) These plumes (darker green) are typically situated near the leading edge of polar cold fronts.
3) P-3 aircraft documented strong water vapor flux in a narrow (400 km-wide) AR; See section AA'.
4) Airborne data also showed 75% of the vapor flux was below 2.5 km MSL in vicinity of LLJ.



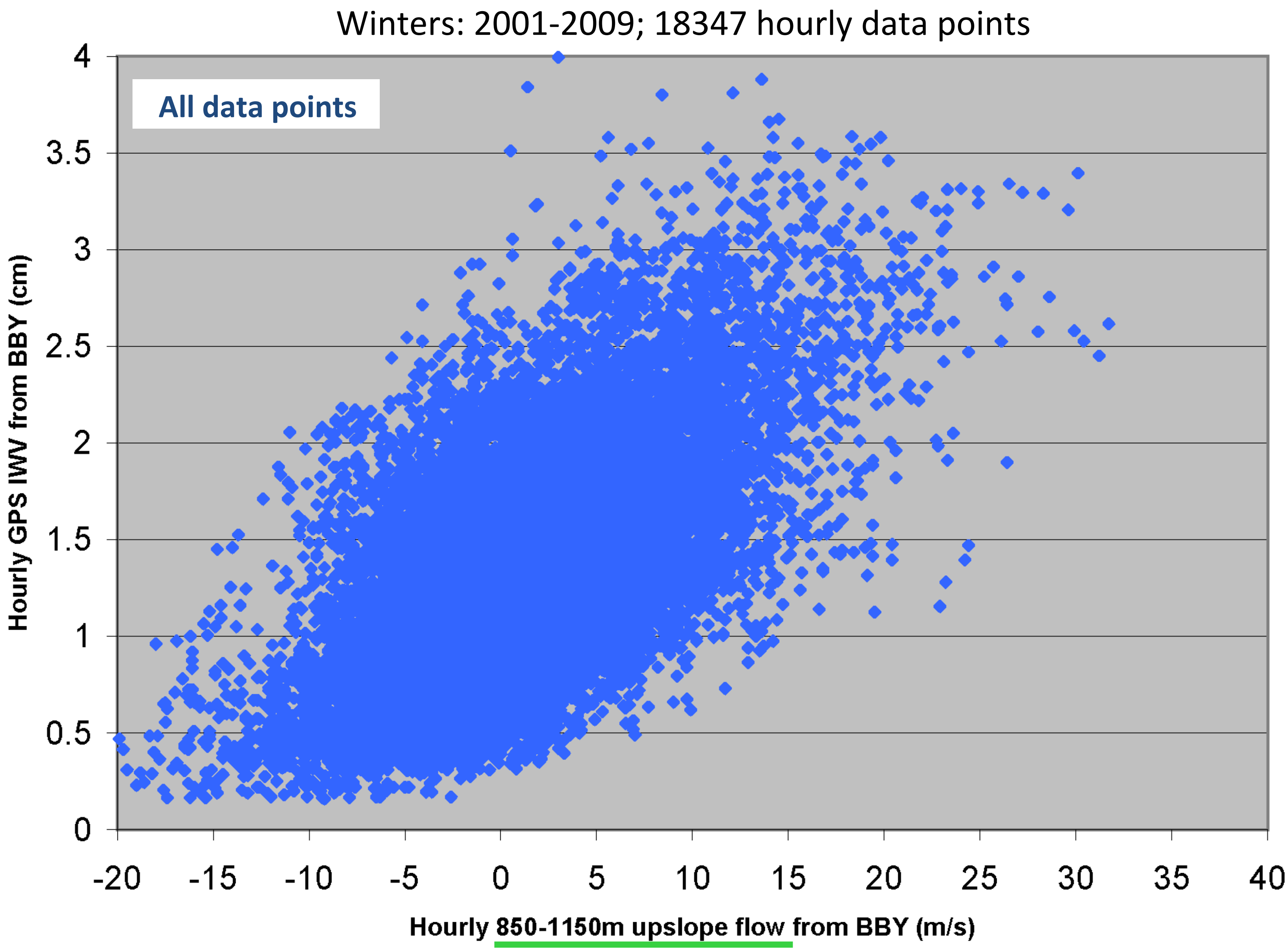


When atmospheric rivers strike coastal mountains (Ralph et al. 2003)

➢Details (e.g., wind direction) of the atmospheric river determine which watersheds flood

Thresholds in water vapor and wind are key in determining heavy hourly rainfall

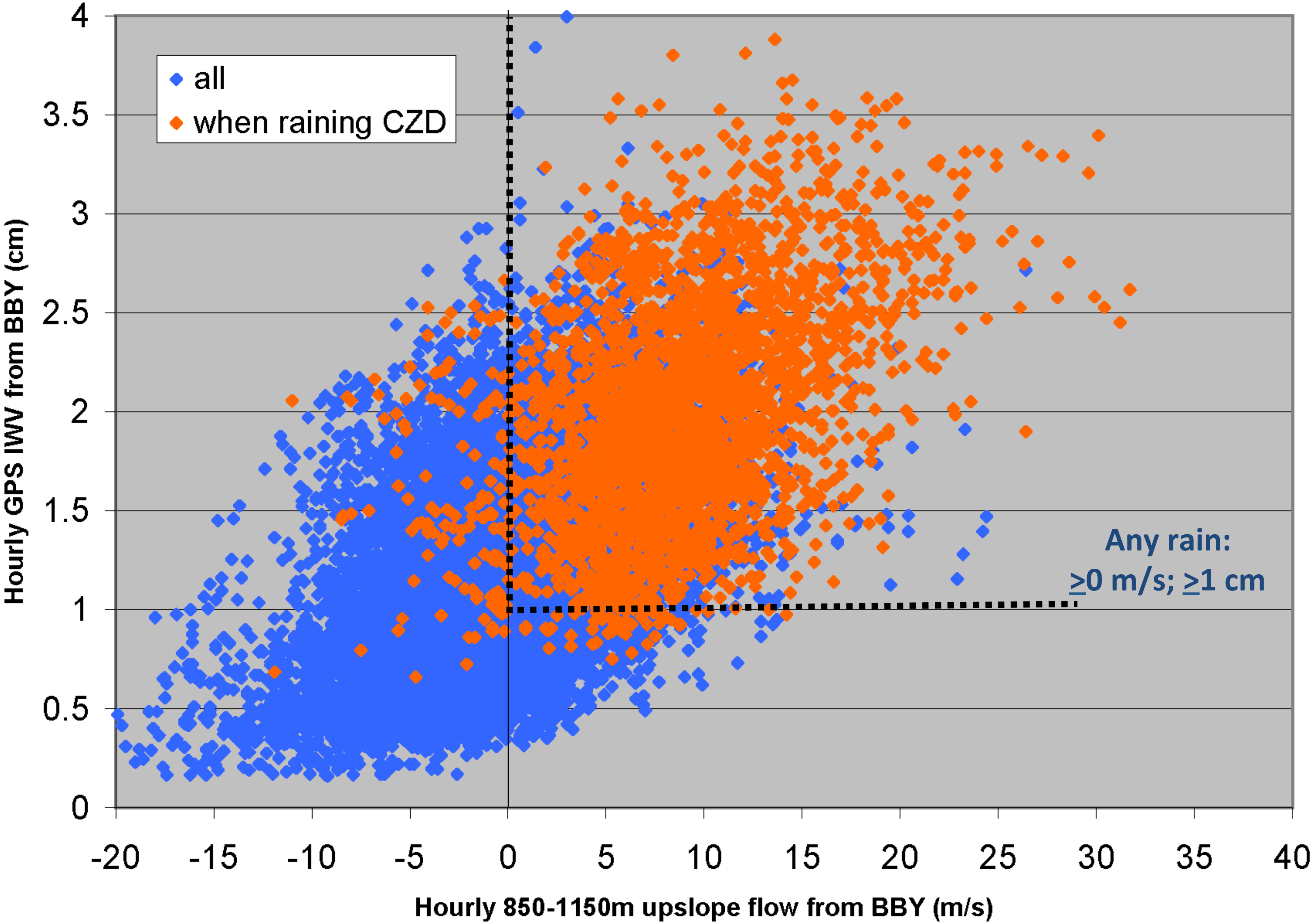
- The next 4 graphs each show 8 winters of hourly observations from an atmospheric river observatory near Bodega Bay operated in HMT.
- Over 18,000 hourly measurements of
  - Water vapor
  - Winds at 1 km above sea level
  - Coastal mountain rainfall

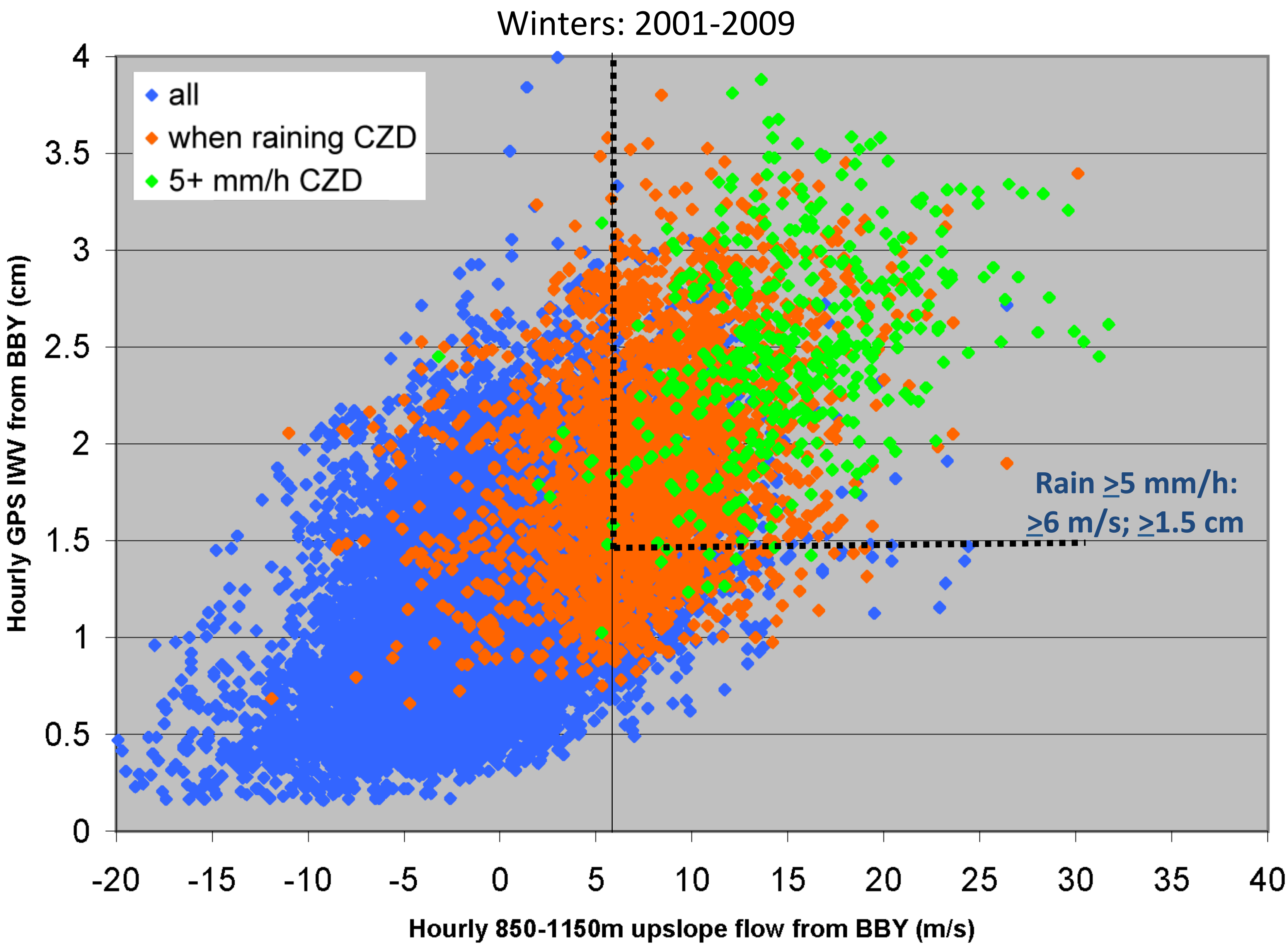


Component of the flow in the orographic controlling layer directed from 230°, i.e., orthogonal to the axis of the coastal mtns

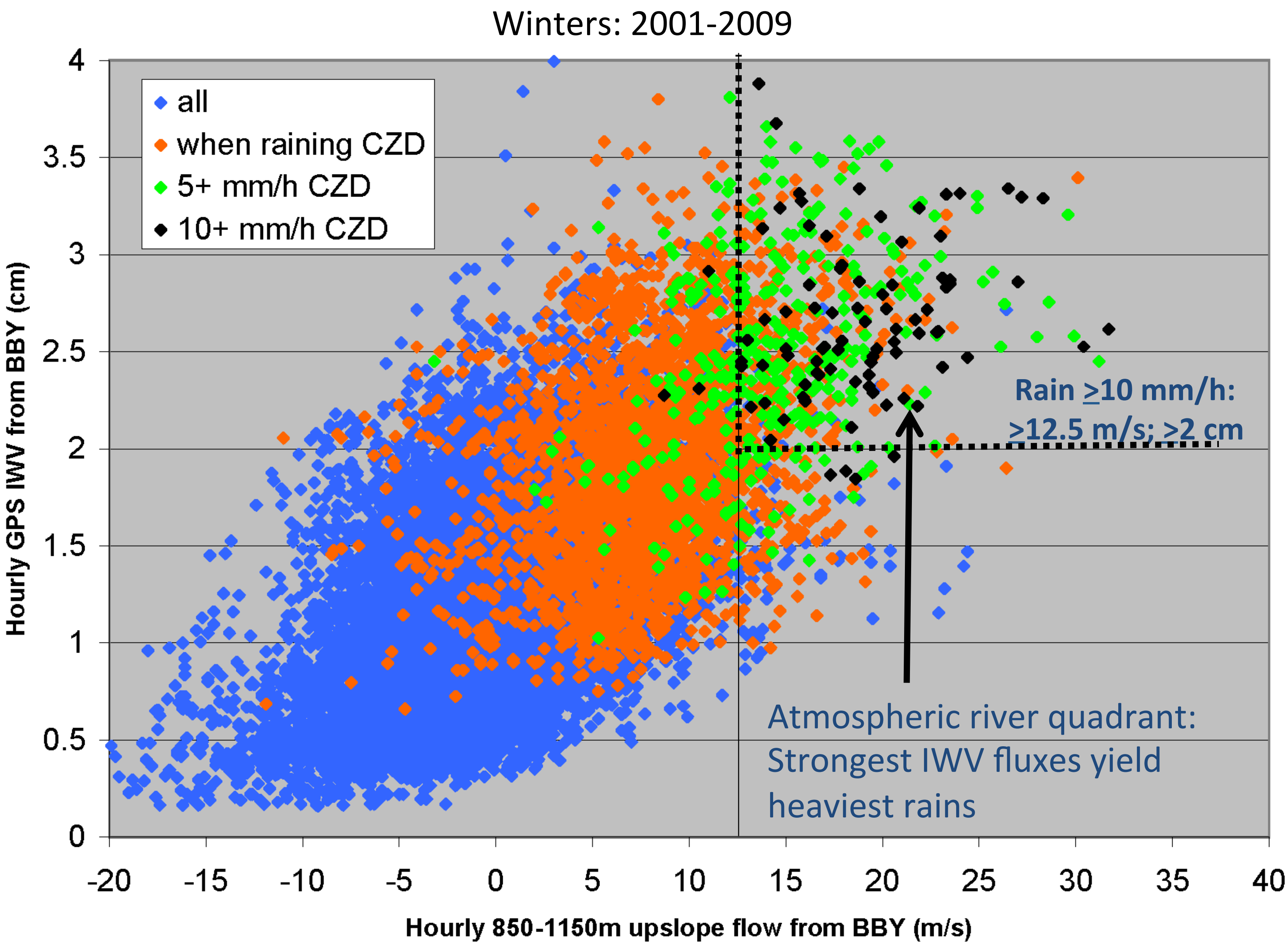
Neiman et al. (2008), *Water Management*

Winters: 2001-2009





Winters: 2001-2009
all
when raining CZD
5+ mm/h CZD
Rain ≥5 mm/h:
≥6 m/s; ≥1.5 cm
Hourly GPS IWV from BBY (cm)
Hourly 850-1150m upslope flow from BBY (m/s)
0
0.5
1
1.5
2
2.5
3
3.5
4
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40



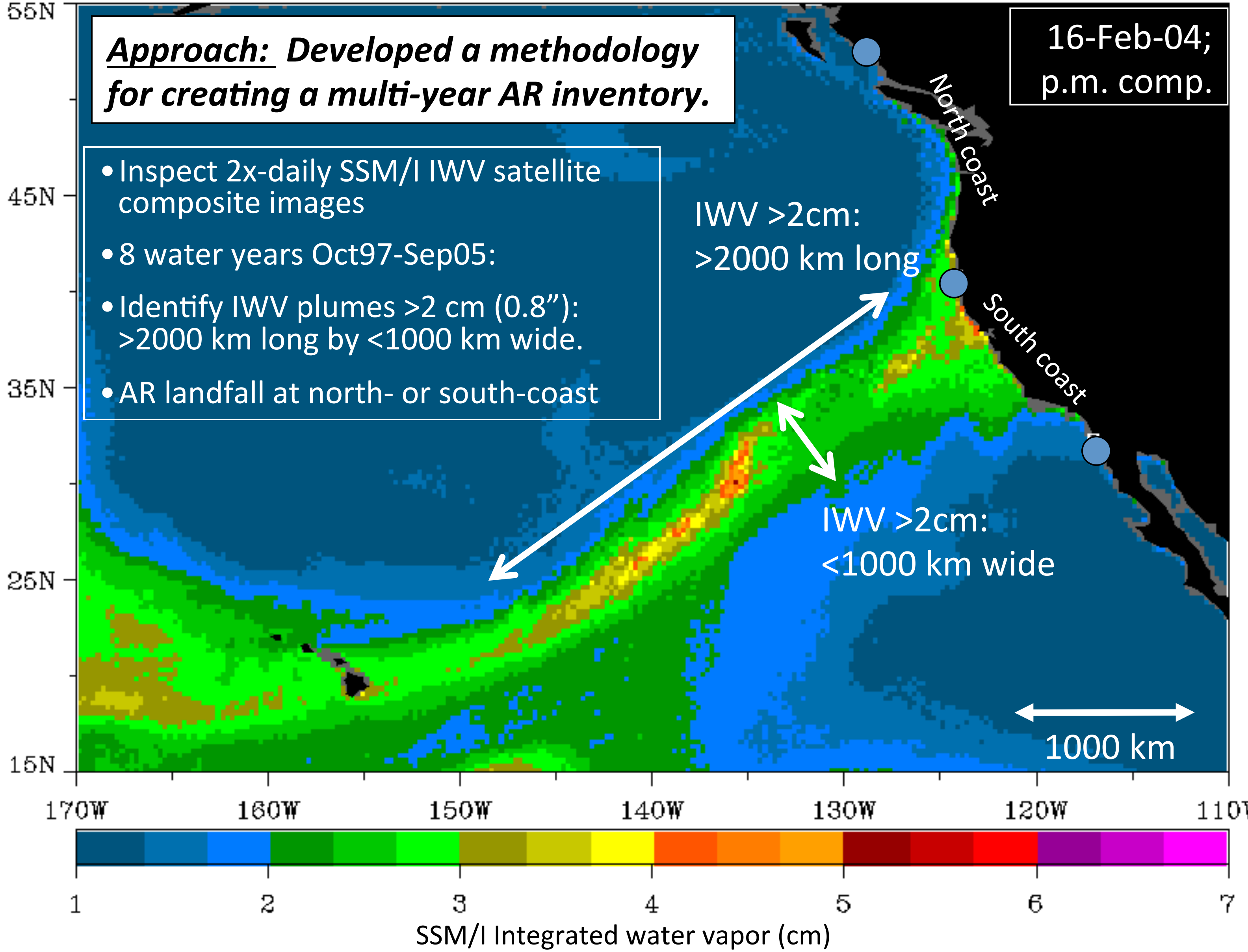
*Nearly 2/3 of tropospheric water vapor is in the lowest 2 km MSL.
Hence, to first order, the IWV flux provides a close estimate
of the low-level water-vapor transport into the coastal mountains.

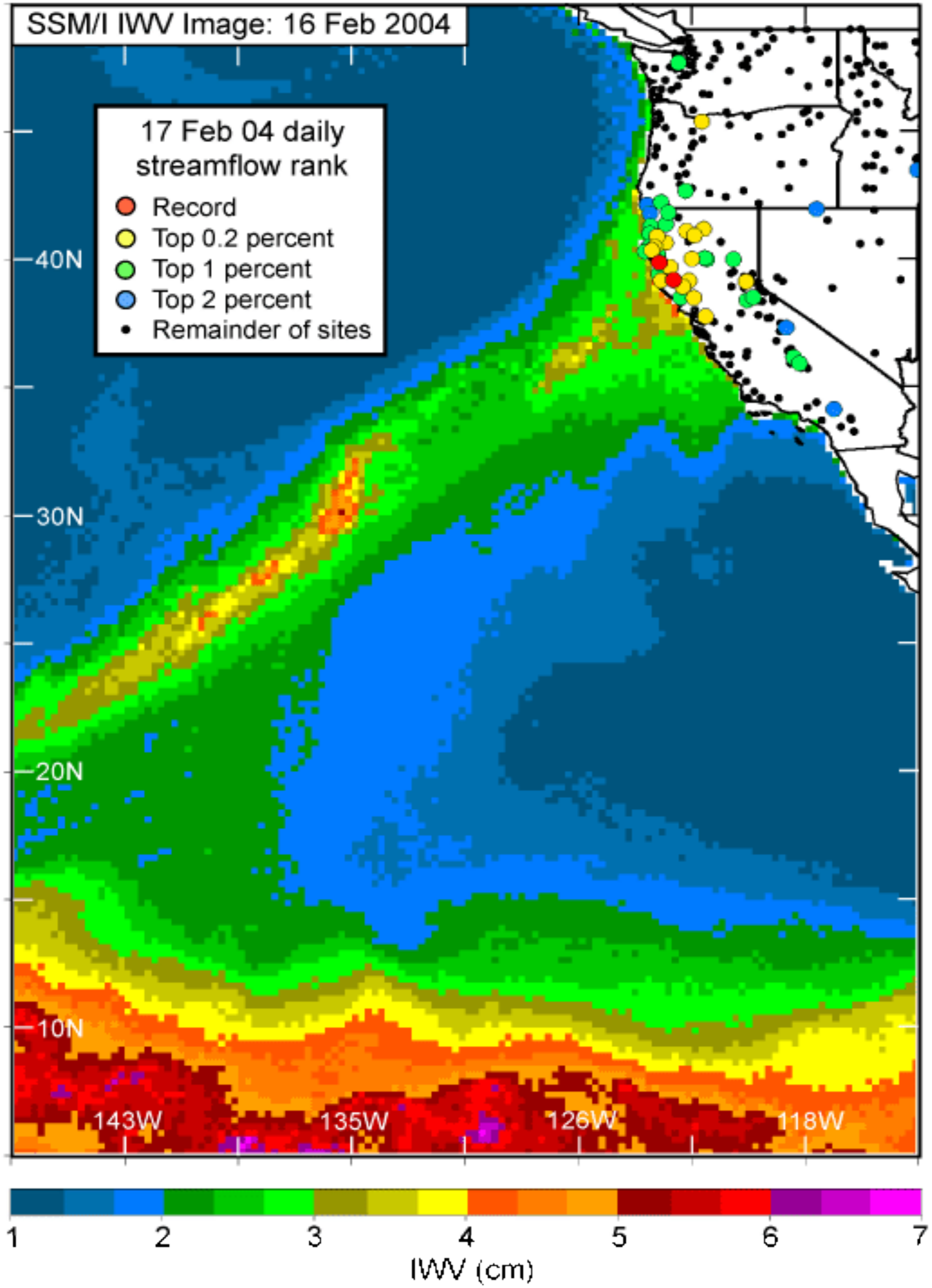
Physical variables required for extreme precipitation (includes AR conditions)

- Wind in the controlling layer near 1 km MSL
  - speed > 12.5 m/s
  - direction (determines location of rain shadow)
- Water vapor content
  - vertically integrated water vapor (IWV) > 2 cm
- Snow level
  - Above top of watershed

Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations

Neiman, P.J., F.M. Ralph, G.A. Wick, J. Lundquist, and M.D. Dettinger (2008), *J. Hydrometeor.*, **9**, 22-47.





Flooding on California's Russian River: Role of atmospheric rivers

Ralph, F.M., P. J. Neiman, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, A. White

Geophys. Res. Lett., 2006

- SSM/I satellite image shows atmospheric river
- Stream gauge data show regional extent of high stream flow Covering roughly 500 km of coast

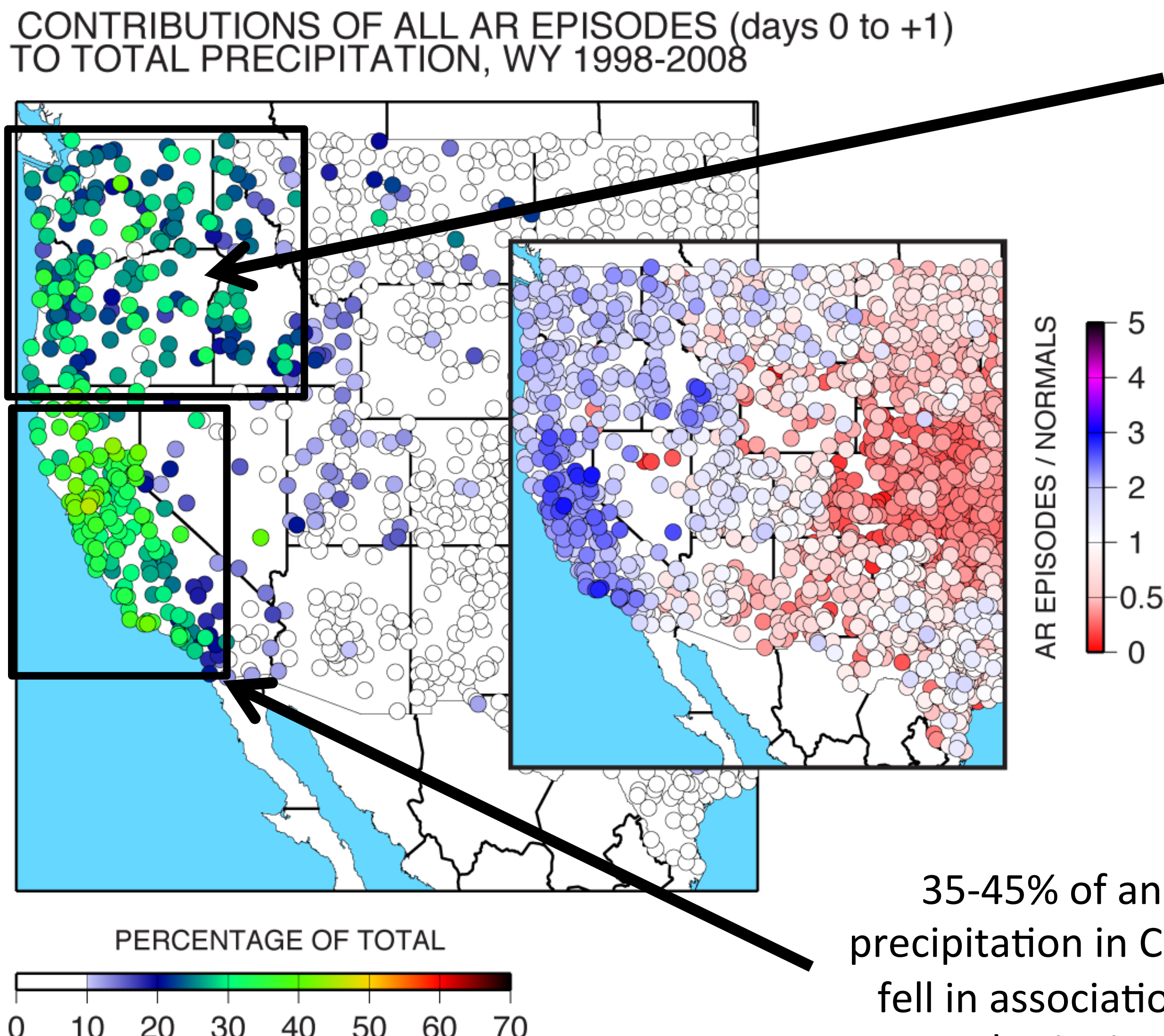
This paper showed that flooding on the Russian River is associated with atmospheric rivers (all 7 floods over 8 years).

If a strong AR stalls for 12-36 hours, it can create flooding.

Atmospheric Rivers, Floods and the Water Resources of California

by Mike Dettinger, Marty Ralph, , Tapash Das, Paul Neiman, Dan Cayan

Water, 2011



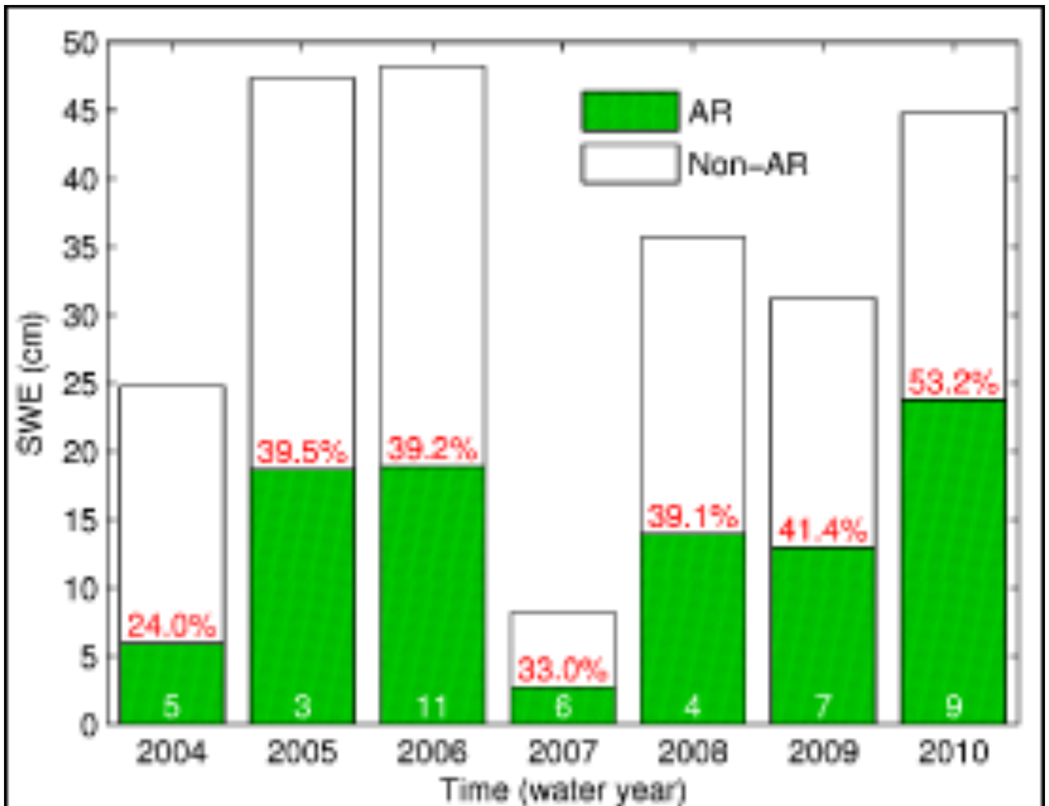
25-35% of annual precipitation in the Pacific Northwest fell in association with atmospheric river events

35-45% of annual precipitation in California fell in association with atmospheric river events

Extreme Snowfall Events Linked to Atmospheric Rivers and Surface Air Temperature via Satellite Measurements

Bin Guan, Noah P. Molotch, Duane E. Waliser, Eric J. Fetzer, and Paul J. Neiman
Geophysical Research Letters, **37**, L20401.

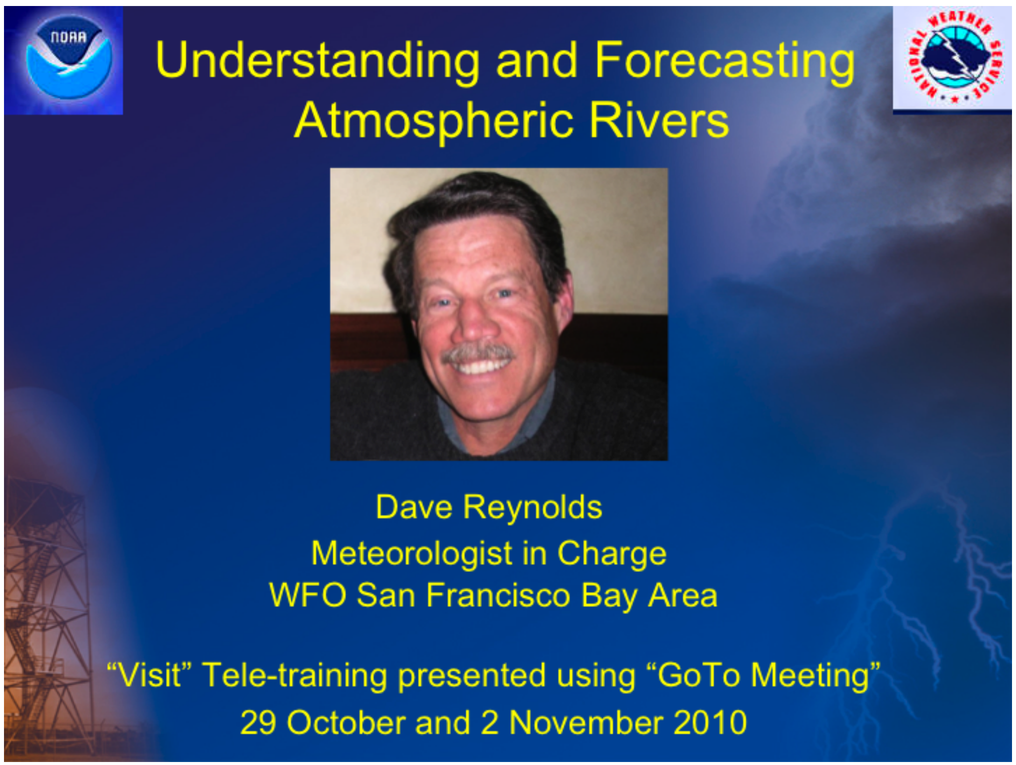
- ***On average 6-7 AR events provided 30-40% of total seasonal SWE accumulation in most years, dominated by 1-2 extreme events in some cases.***



- ARs generated ~4 times as much daily SWE accumulation compared to non-AR events for 2004-10.
- Colder (warmer) surface air temperature was observed for high (low)-impact ARs.

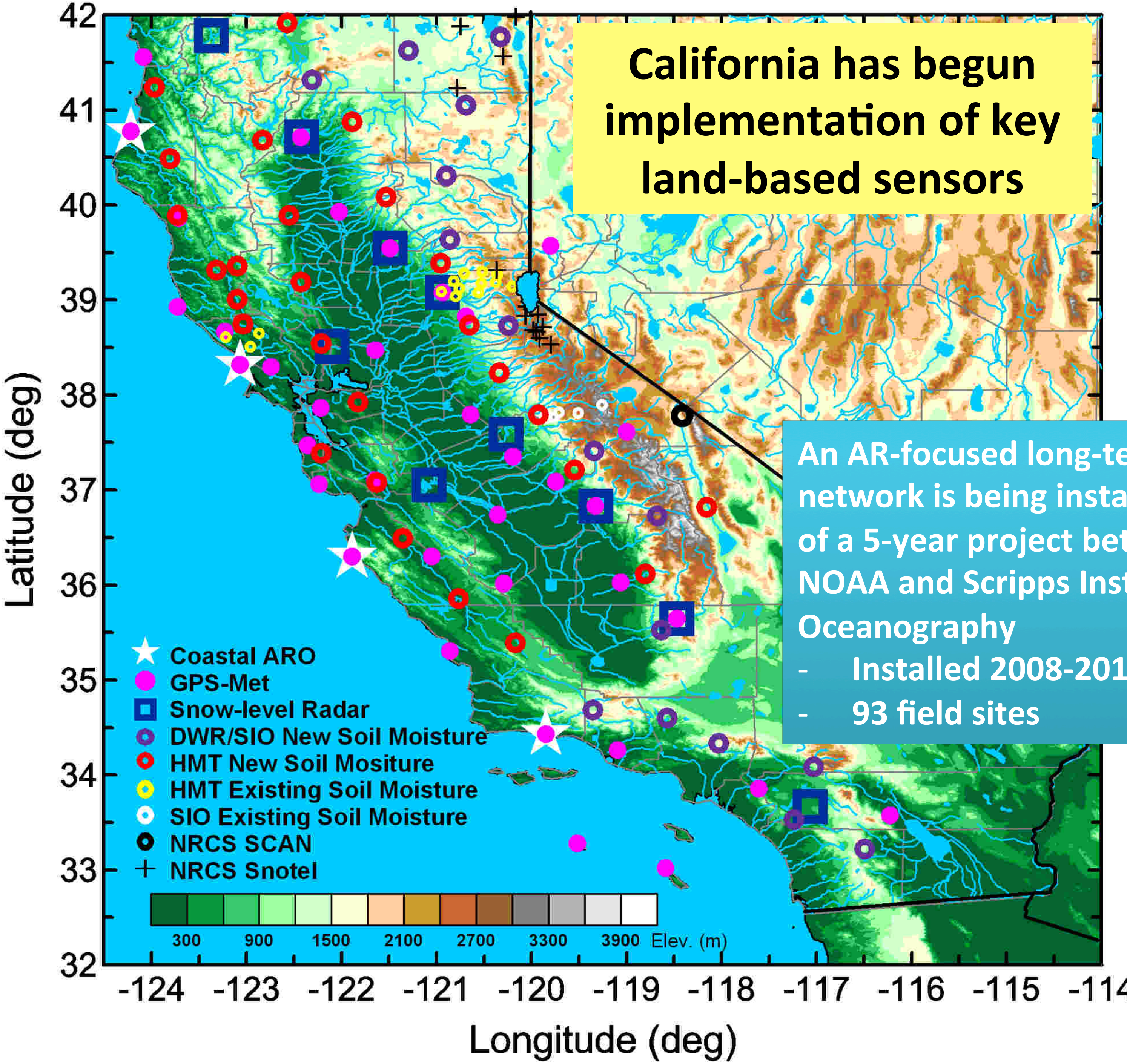
Forecasting Atmospheric Rivers

HMT Findings used in NWS Training



- Improved situational awareness
- Advance lead time that a "big event" may be coming, a few days ahead
- Details on locations, timing and strength improve as event nears, but precipitation amounts are generally underpredicted

California has begun implementation of key land-based sensors

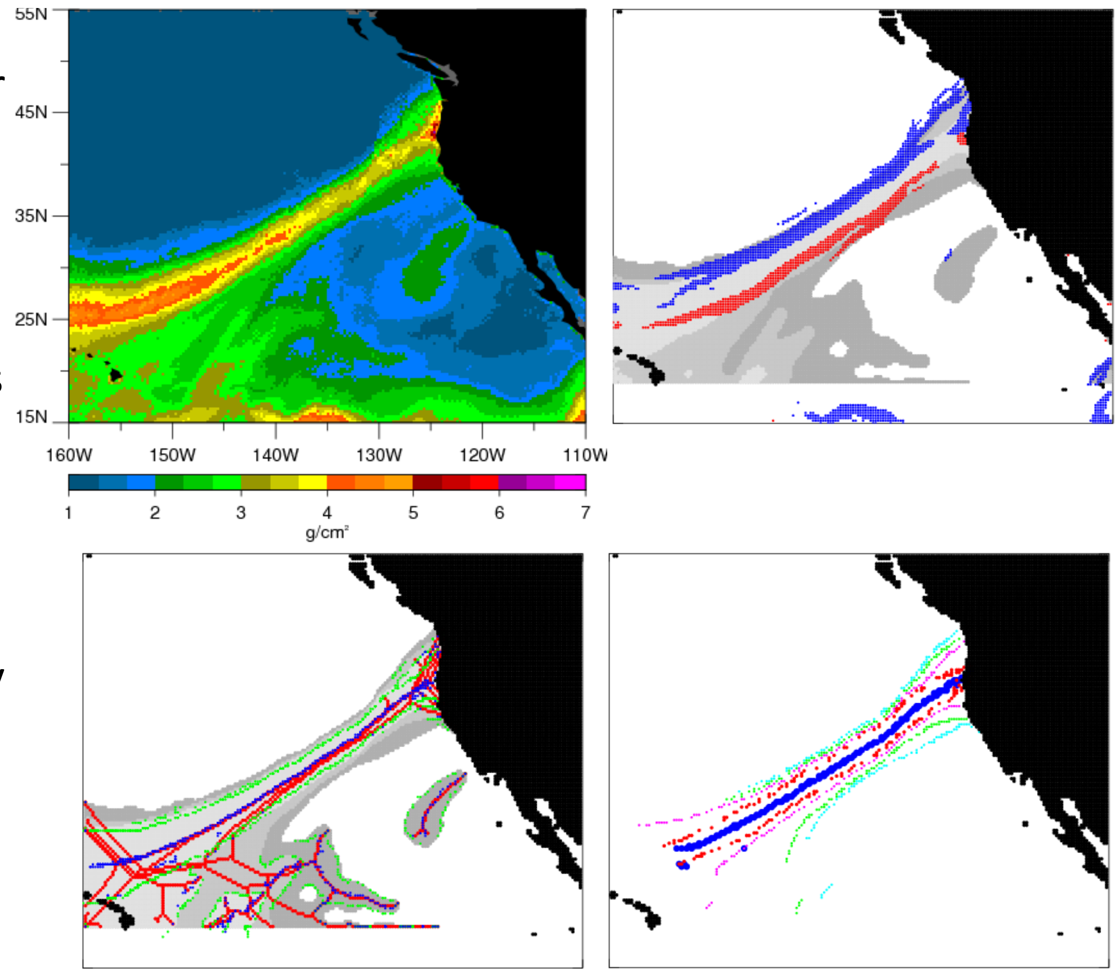


An AR-focused long-term observing network is being installed in CA as part of a 5-year project between CA-DWR, NOAA and Scripps Inst. of Oceanography

- Installed 2008-2012
- 93 field sites

Objective AR Identification Procedure

- Isolate top of the tropical water vapor reservoir
- Threshold IWV values at multiple levels and compute gradients
- Cluster points above thresholds and compute skeleton to estimate axis
- Identify points satisfying width criteria
- Cluster center points to identify segments of sufficient length
- Extract AR characteristics
- Determine if AR intersects land or is potentially influenced by data gaps

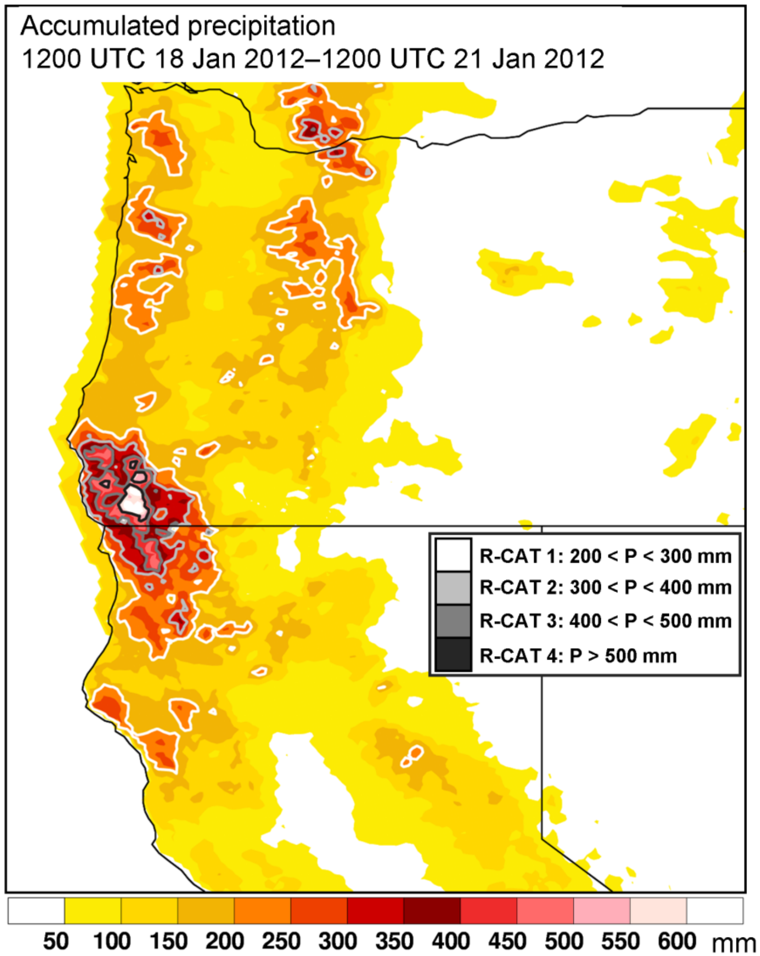


Example from November 7, 2006

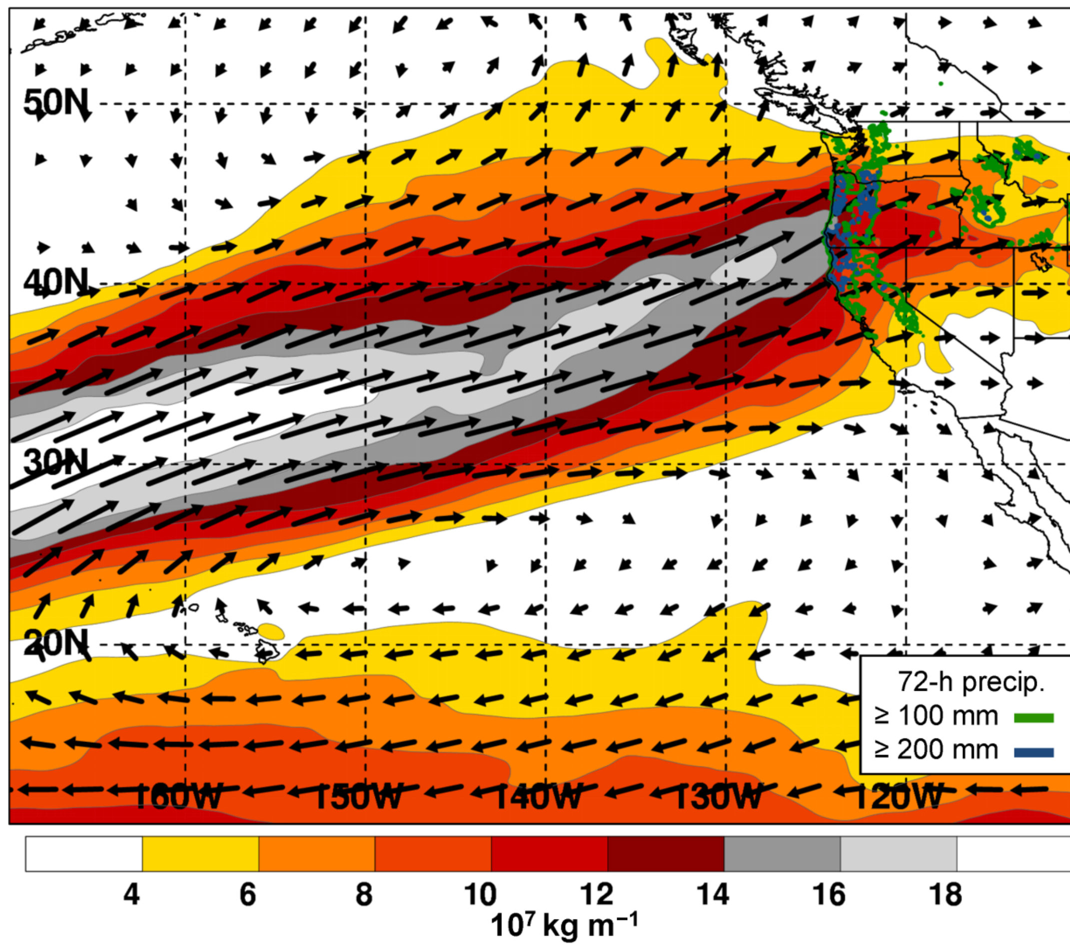
Wick et al., 2012, IEEE TGRS, in revision.

18–21 Jan 2012 AR Event

- The long duration of AR conditions in Oregon and northern California supported widespread heavy rainfall
- 72-h precipitation totals exceeding 100 mm were common along the west coast, with largest amounts observed in southwestern Oregon and northwestern CA
- Localized precip. totals ranging from 400 mm to >500 mm (R-CATs 3–4) were observed in this region



Time-integrated IVT 12 UTC 18 Jan–12 UTC 21 Jan



CalWater Experiment

M. Ralph, K. Prather, D. Cayan (EOS, September 2011)

Exploring key geophysical processes influencing water supply and extreme precipitation in a changing climate on the U.S. West Coast

- CalWater is a multi-year (2008-2012), multi-agency research project with two primary research themes:
  - the impact of changing climate on atmospheric rivers (AR) and associated extreme events, and
  - the potential role of aerosols in modulating cloud properties and precipitation, especially regarding orographic precipitation and water supply.
- Advances made in CalWater have implications for both water supply and flood control in California and other west coast areas, both in the near term and in a changing climate.
- CalWater is a continuation of prior studies on the role of aerosols on climate sponsored by the California Energy Commission (CEC) and heavily leverages observations and research on extreme precipitation in NOAA's Hydrometeorology Testbed (HMT; hmt.noaa.gov).

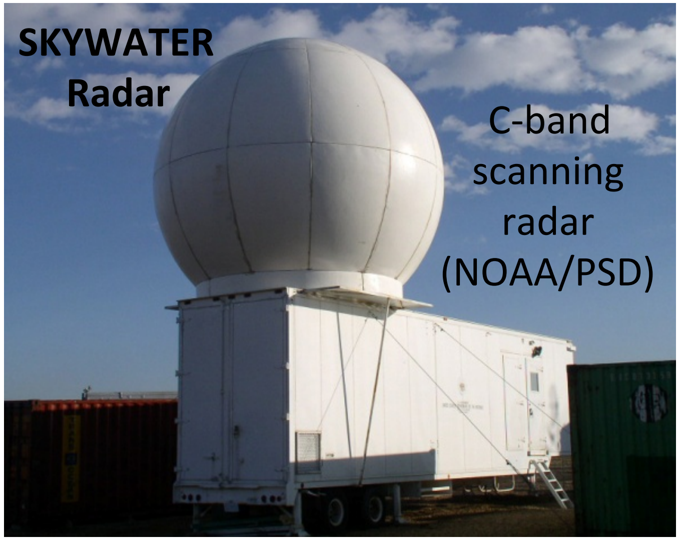
CalWater & HMT-West Observing Systems Winter 2010/2011 in California Experiments documenting ARs


Three S-Prof precipitation profilers (NOAA/PSD)


G-1 Research aircraft for CalWater (DOE/PNNL)
1 Feb – 7 mar 2010


449 MHz wind profiler

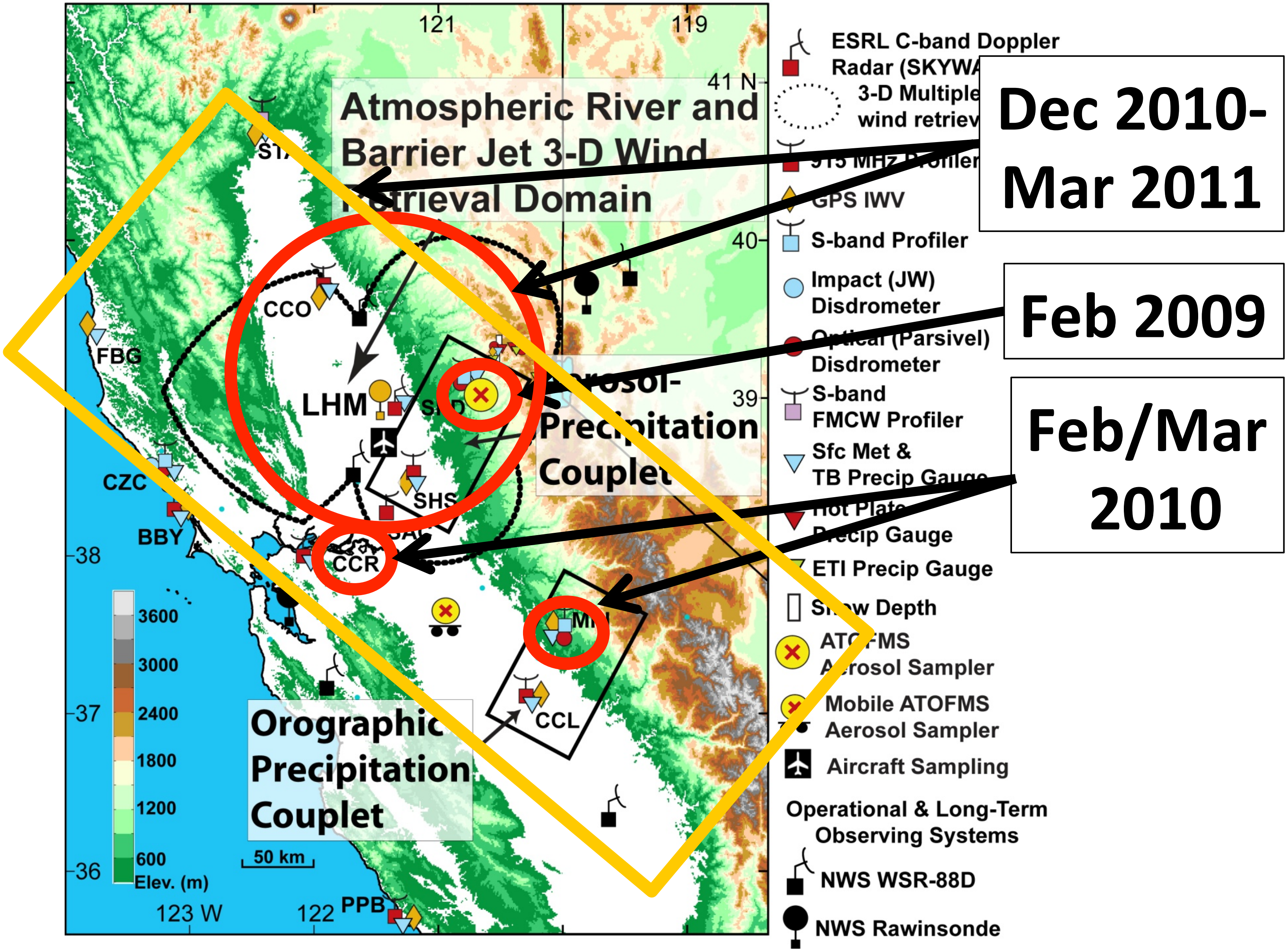
GPS IWV & balloon Sounding Systems


SKYWATER Radar

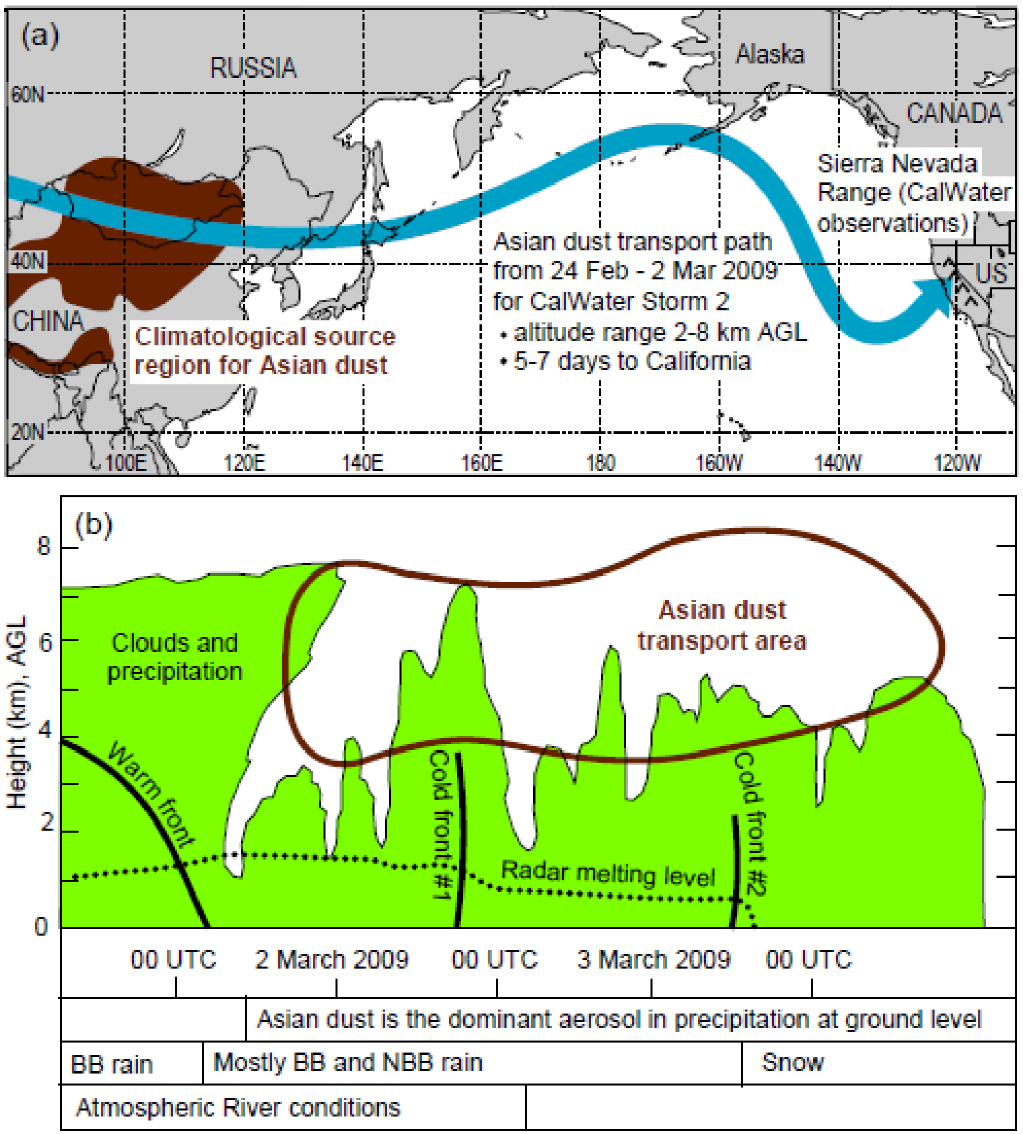
C-band scanning radar (NOAA/PSD)


Seven 915 MHz wind profilers (NOAA/PSD)

CalWater and Key HMT Observing Sites - Winter 2011

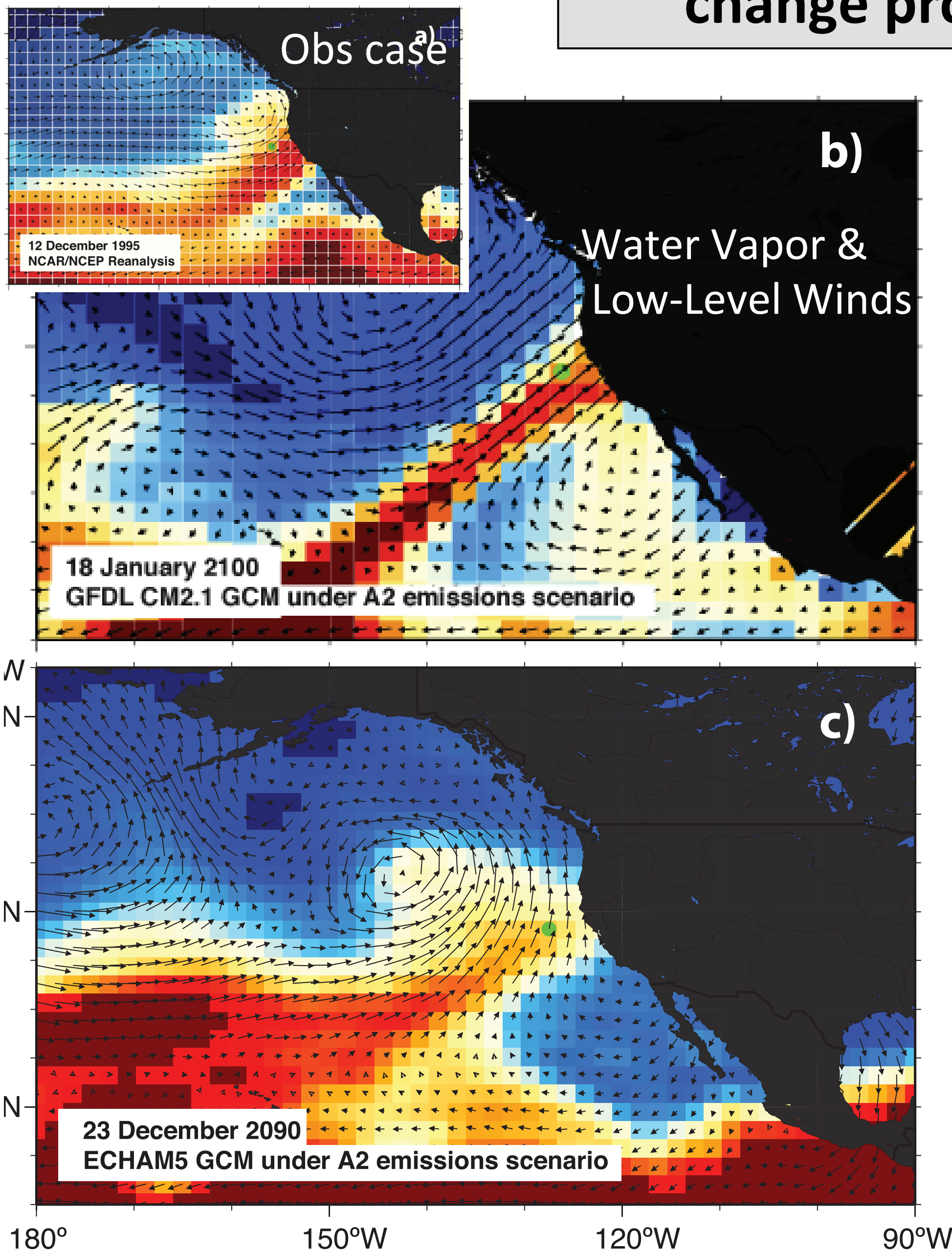


Potential Impacts of Aerosols on California Precipitation and Water Supply



- **CalWater** field experiment has documented a potentially important role of Asian dust and related aerosols on Sierra Nevada precipitation
- CalWater involves CEC, NOAA, SIO, DOE, NASA, and other partners
- Initial results published in JGR Sept 2011 (Ault et al.)
- 40% greater precipitation in a storm with Asian dust and aerosols versus a very similar storm without them

Atmospheric Rivers in IPCC-AR4 climate-change projections by 7 modern GCMs



By end of 21st Century, most GCMs yield:

- **More atmospheric vapor content, but weakening westerly winds**

→Net increase in "intensity" of extreme AR storms

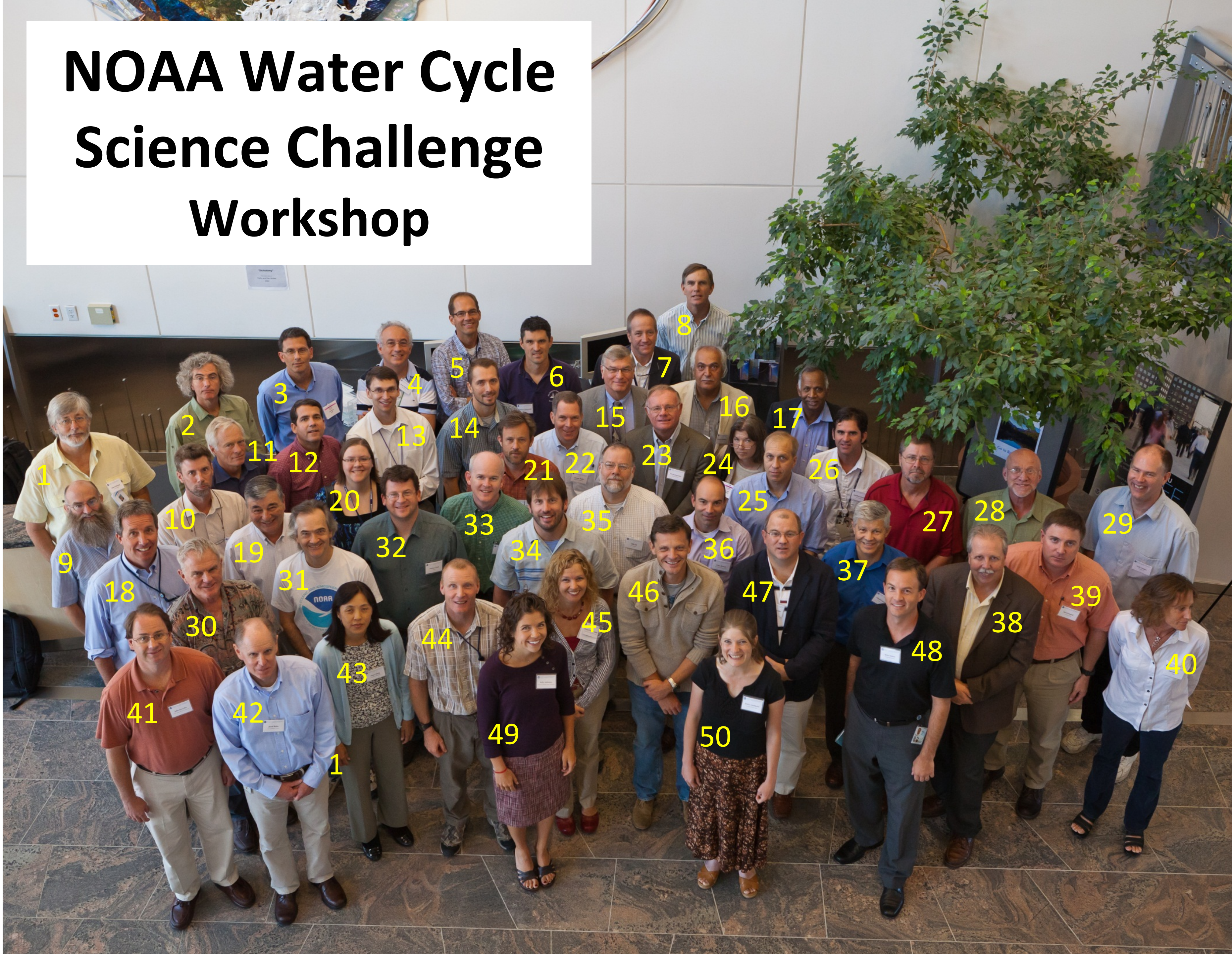
- **Warmer ARs (+1.8 C) → snowline raised by about 1000 feet on average**

- **Lengthening of AR seasons (maybe?)**

Dettinger, M.D., 2011, Climate change, atmospheric rivers and floods in California—A multimodel analysis of storm frequency and magnitude changes: Journal of American Water Resources Association, 47, 514-523.

Water Cycle Science Gaps

NOAA Water Cycle Science Challenge Workshop



NOAA Water Cycle Science Challenge Workshop

- **Scope**
  - "Understanding & predicting conditions associated with too much or too little water"
  - Interagency Program Committee: Marty Ralph (NOAA) , Bert Davis (USACE) Co-chairs
  - More than 60 people (1/3 NOAA, 1/3 other Agencies, 1/3 Academic) for 3 days

- **Key Recommendations**
  - Increase hydrologic forecasting skill for low-to-high flow conditions to be as good as the skill afforded by weather and climate predictions
  - Develop a National Water Cycle Reanalysis, including key "forcings" that close the water budget at multiple temporal and spatial scales
  - Diagnose physical processes key to extreme events and document their roles in forecast successes and busts
  - Develop a Hydroclimate Testbed building on NIDIS, HMT, RISAs and Labs that would link hydroclimate science to services and user needs, and emphasizes extremes

Extreme events, water hazards and water supply

Speaker: Marty Ralph (NOAA)

Co-authors: Michael Hanemann (UC Berkeley, Arizona State U)

Ben Brooks (U. of Hawaii)

Mike Dettinger (USGS and Scripps/UCSD)

Dan Cayan (UCSD/Scripps and USGS)

Konstantine Georgakakos (HRC)

Jay Lund (UCD)

Jay Famiglietti (UCI)

Michael Anderson (DWR)

Jeanine Jones (DWR)

Presented at "Vulnerability and Adaptation to Extreme Events in California in the Context of a Changing Climate: New Scientific Findings"

Scripps Institution of Oceanography, La Jolla, California
13 December 2011

Conclusions

- California has significant vulnerabilities to shifts in extreme precipitation and runoff
- Reduced snow pack is a key risk to water supply, as are reductions in Colorado River flow and inundation of the Delta
- Changes in the strength of atmospheric rivers and in snow level are key to future flood risks
- Improving monitoring and prediction of critical hydrometeorological conditions can enable adaptation to a changing climate such as by modernizing reservoir operations methods

Thank You

- Atmospheric Rivers Information Page (includes a detailed publication list)
  - www.esrl.noaa.gov/psd/atmrivers/
- CalWater web page
  - www.esrl.noaa.gov/psd/calwater/
- HMT web page
  - hmt.noaa.gov
- Marty.Ralph@noaa.gov